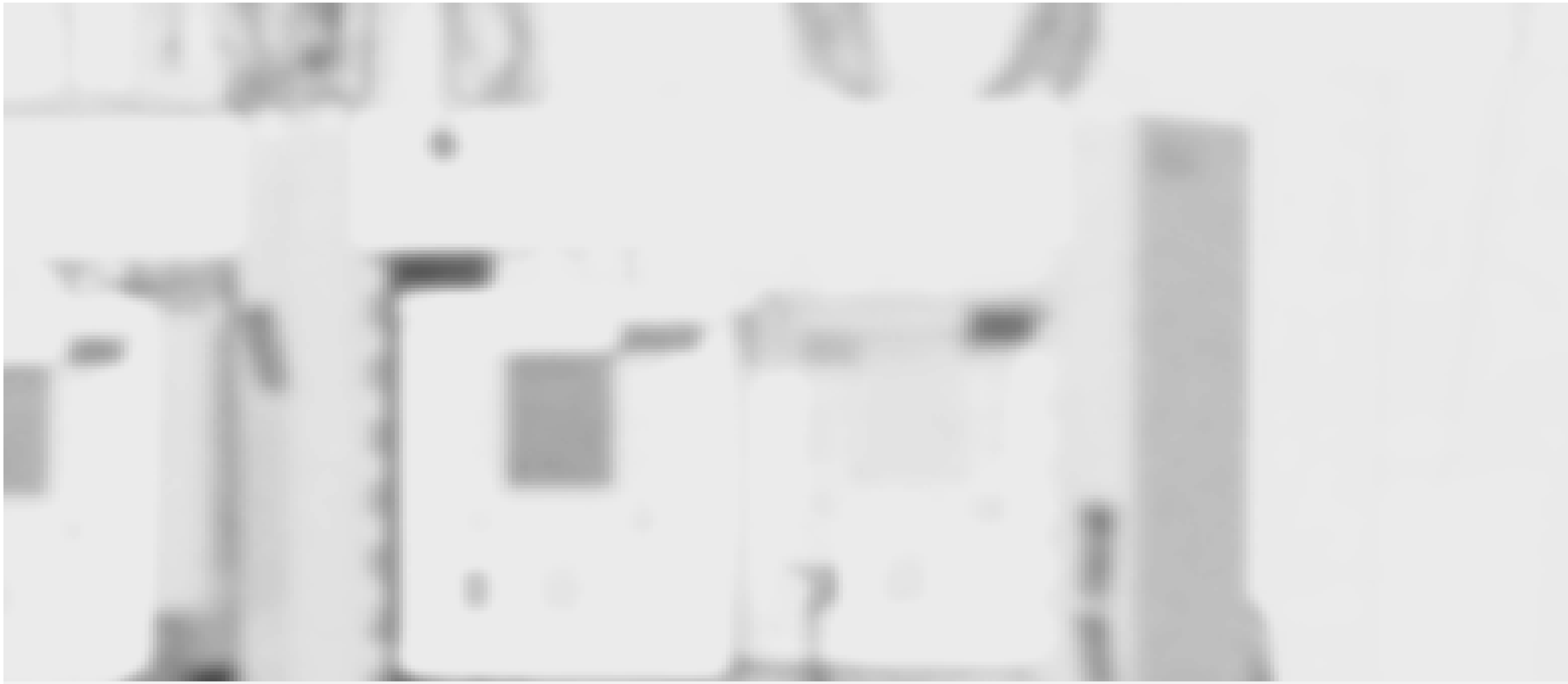


EPFL, Spring 2020

2 Control and Field Level Devices

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

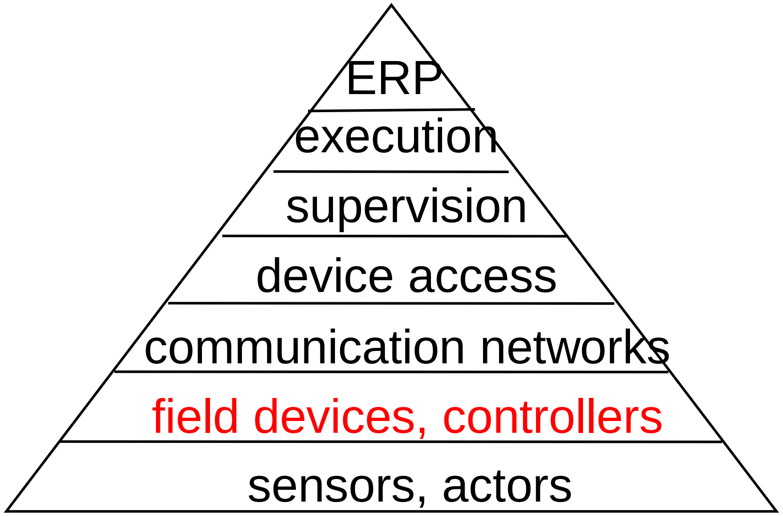
Content

PLC = Programmable Logic Controller: Definition

AP = Automates Programmables industriels
SPS = Speicherprogrammierbare Steuerungen

Definition:	“small computers, dedicated to automation tasks in an industrial environment"
Formerly:	cabled relay control (hence 'logic'), analog (pneumatic, hydraulic) “governors”
Today:	real-time (embedded) computer with extensive input/output
Function:	Measure, Control, Protect

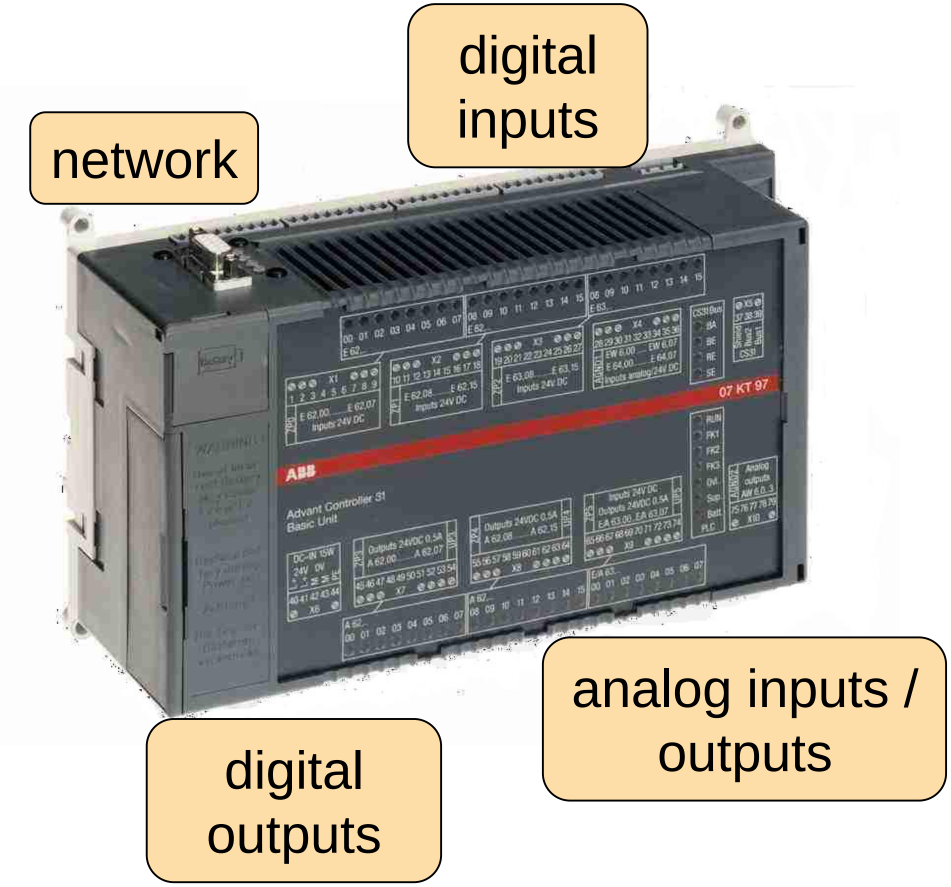
+ Event Logging,
  communication,
  human machine interface (HMI)



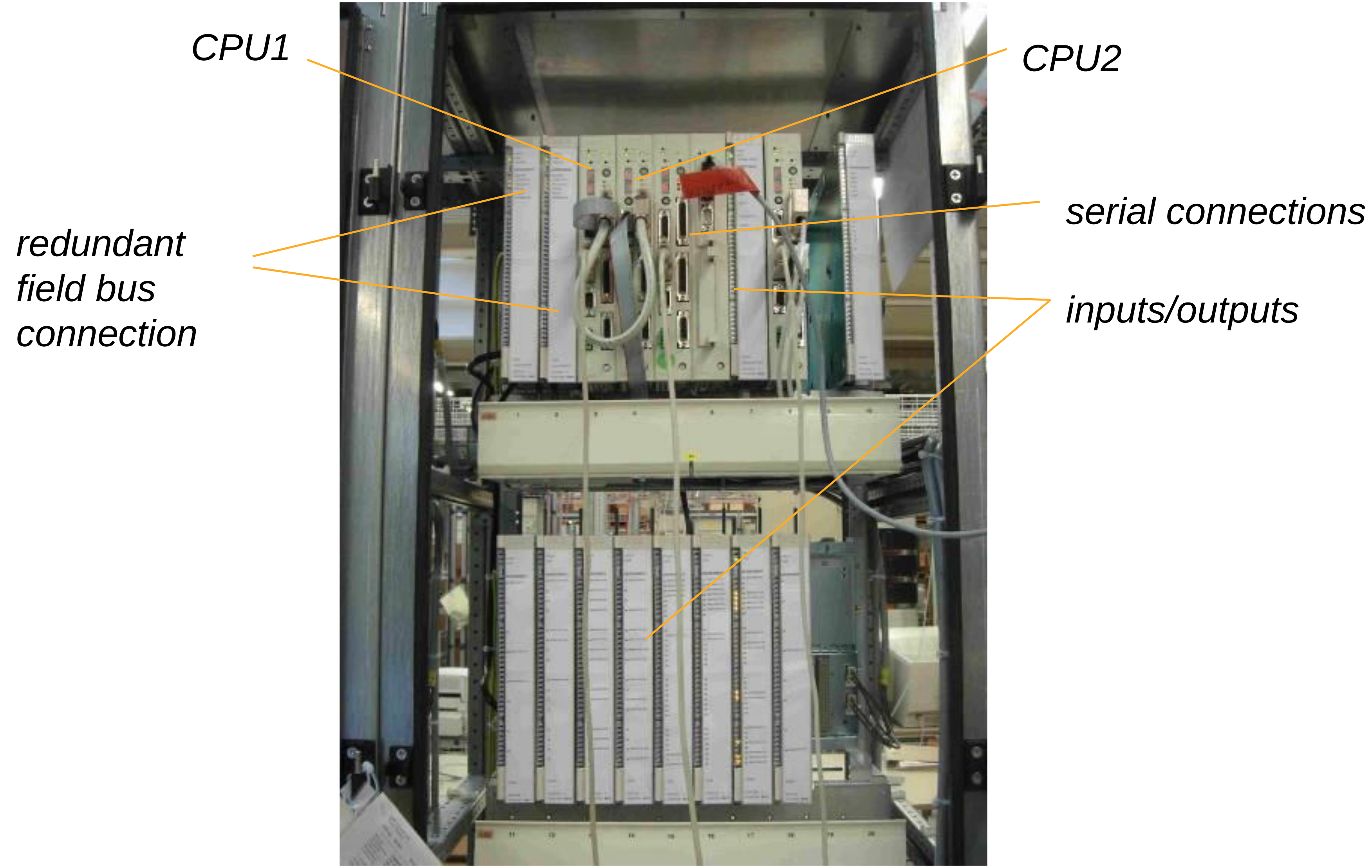
Simple PLC

Main components in a PLC can be categorized into:

- Processor (CPU, etc.)
- Input (digital, analog, etc.)
- Output (digital, analog, etc.)



PLC in a cabinet



PLC: Characteristics

• large number of peripherals: 20..100 I/O per CPU, high density of wiring.

• digital and analog input/output with standard levels

• field bus connection for remote I/O.

• operate under harsh conditions, require robust construction, protection against dirt, water, mechanical threats, electro-magnetic noise, vibration, extreme temperature range (-30C..85C), sometimes directly located in the field.

• primitive Human-Machine-Interface for maintenance, either through LCD-display or connection of a laptop over serial lines (RS232) or wireless.

Costs:

• economical - €1000.- .. €15'000.- for a full crate.

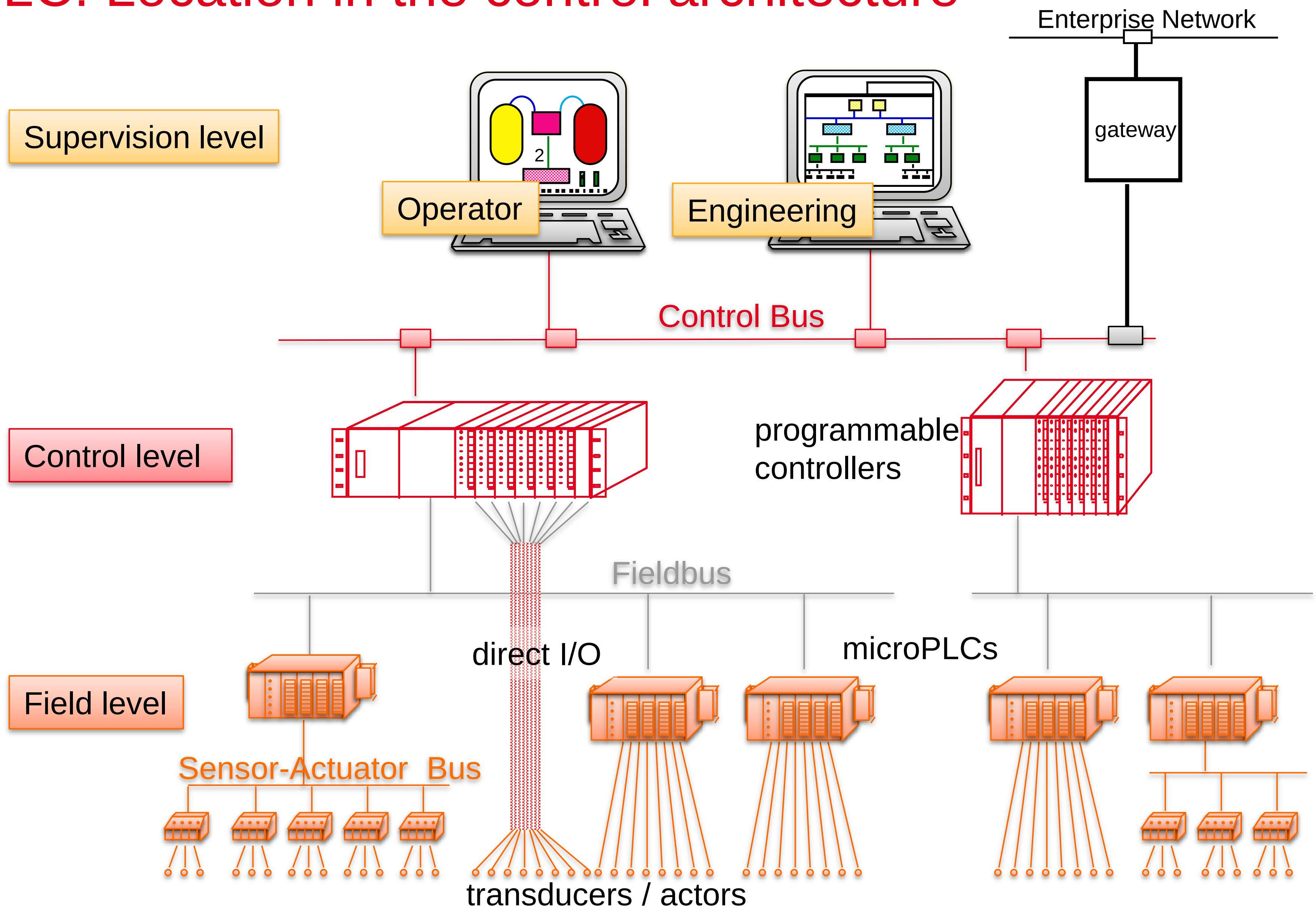
• value is in the application software (licenses €20'000 ..€50'000)

Why 24V / 48 V supply ?

... After the plant lost electric power, operators could read instruments only by plugging in temporary batteries...
[IEEE Spectrum Nov 2011 about Fukushima]

Photo TEPCO

PLC: Location in the control architecture



PLC Programming and Deployment

Programming:

- **Early days**: very primitive with hand-held terminals on the target machine itself
- **More recently**: software developed on a separate computer, then compiled and uploaded on the PLC

PLC software updates:

- Software can be downloaded if PLC supports that feature
- Software changes deployed using engineering workstations/laptops over control bus

Kinds of PLC

(1) Compact

Monolithic construction

(2) Modular PLC

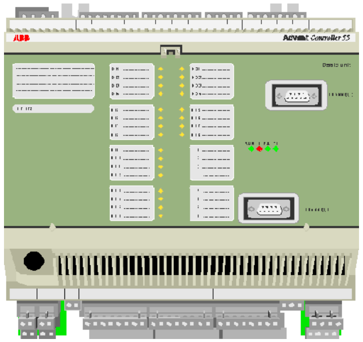
Modular construction (backplane)
Extensible

(3) Soft-PLC

Linux or Windows-based automation products

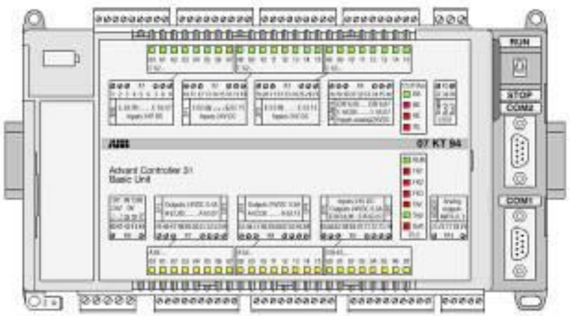
Direct use of CPU or co-processors

Compact PLC



courtesy ABB

courtesy ABB



courtesy ABB

Monolithic (one-piece) construction

- Fixed casing
- No additional processing capabilities
- Fixed number of I/O
  - If more is needed can be extended and networked by an extension (field) bus
- Sometimes LAN connection (Ethernet, Arcnet)

Typical product: Mitsubishi MELSEC F, ABB AC31, SIMATIC S7

costs: € 2000

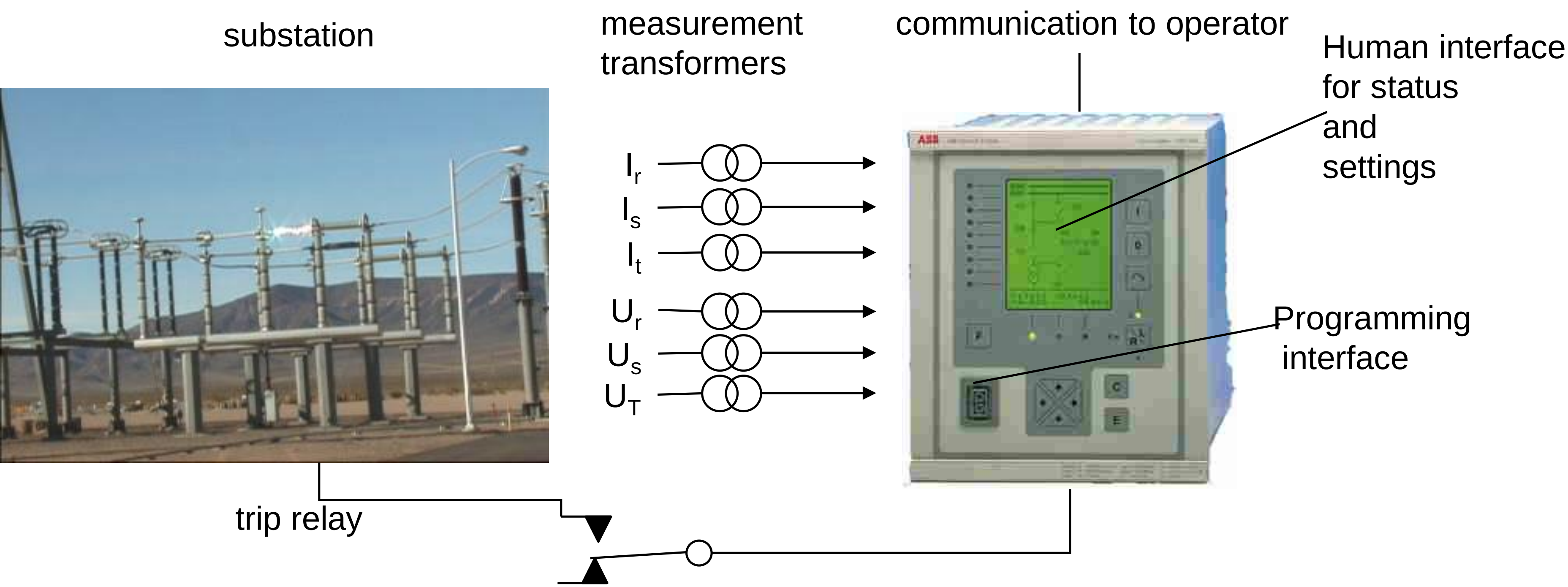
Compact PLC: Specific Controller (example: Turbine)

tailored for a specific application, produced in large series

courtesy Turbec

cost: € 1000.-

Compact PLC: Protection devices

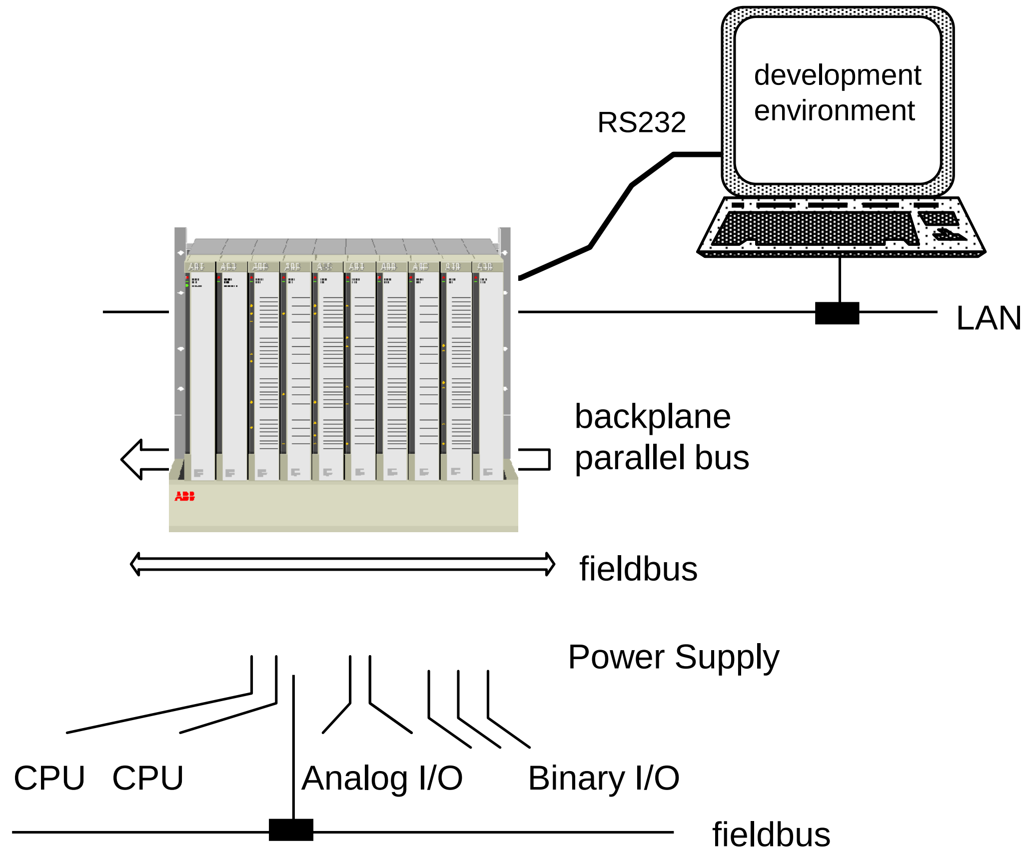


Highly specialized PLCs, measure current and voltages in electrical substation, along with other statuses (position of the switches,…) to detect dangerous situations (over-current, short circuit, overheat) and trigger the circuit breaker (“trip”) to protect the substation.
In addition, they record disturbances and send reports to substation’s SCADA.
Sampling: 4.8 kHz, reaction time: < 5 ms.

costs: € 5000

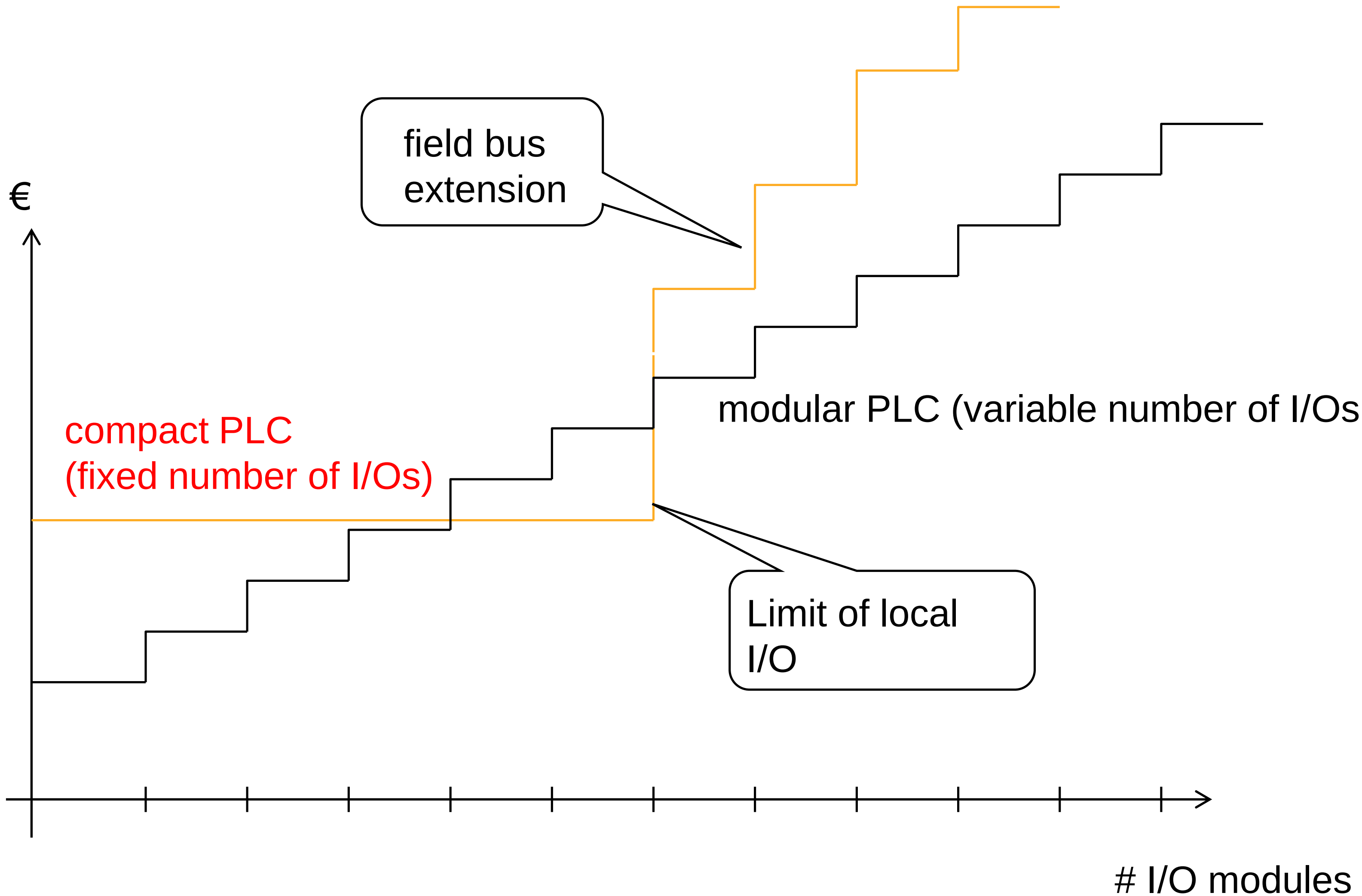
Modular PLC

- can be tailored to needs of application
- housed in a 19" (42 cm) rack
 (height 6U (= 233 mm) or 3U (=100mm)
- high processing power (several CPUs)
- large choice of I/O boards
- concentration of a large number of I/O
- interface boards to field busses
- requires marshalling of signals
- primitive or no HMI
- cost effective if the rack can be filled
- supply 115-230V , 24V or 48V (redundant)
- cost ~ €10’000 for a filled crate



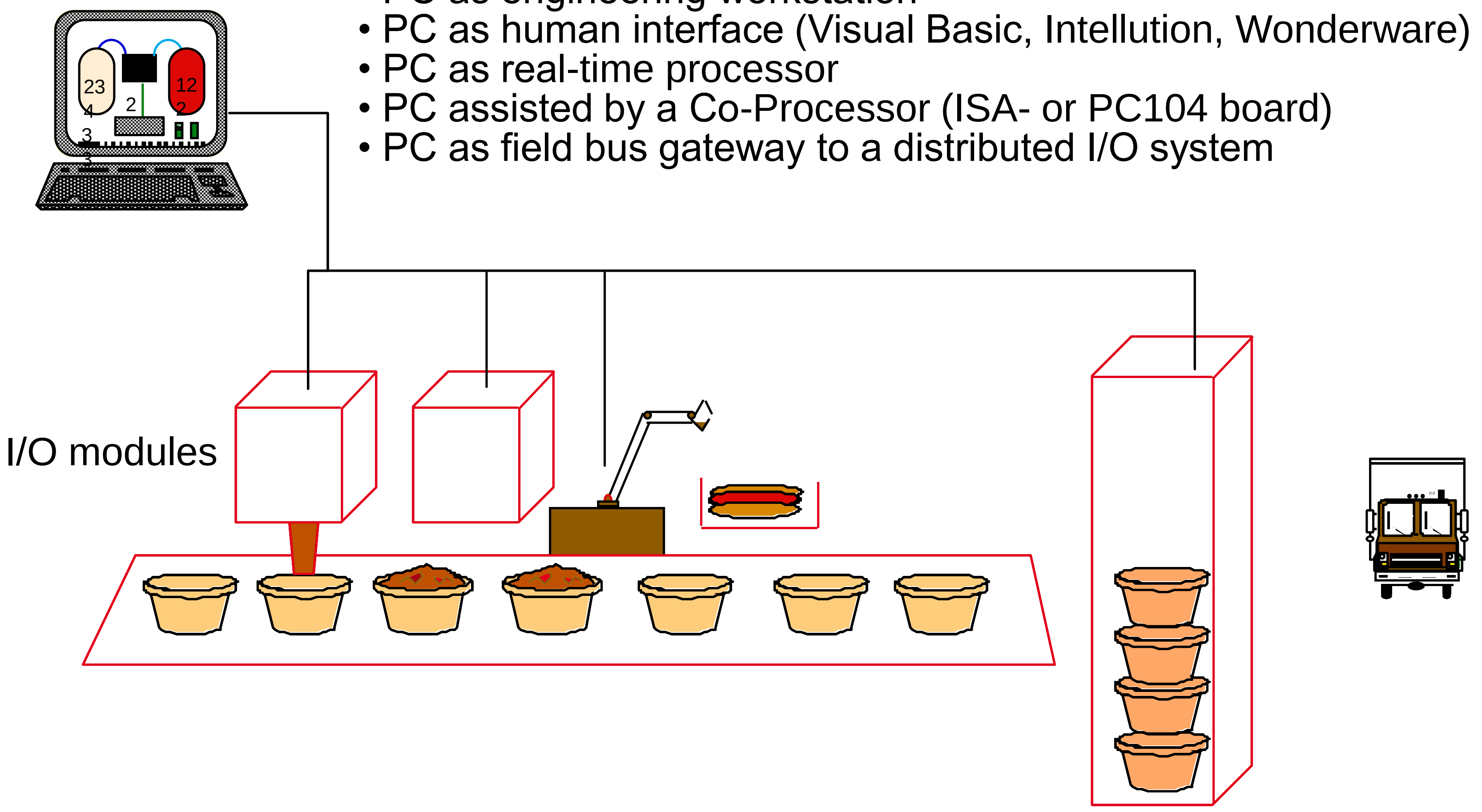
Typical products: SIMATIC S5-115, Hitachi H-Serie, ABB AC110

Compact or modular ?

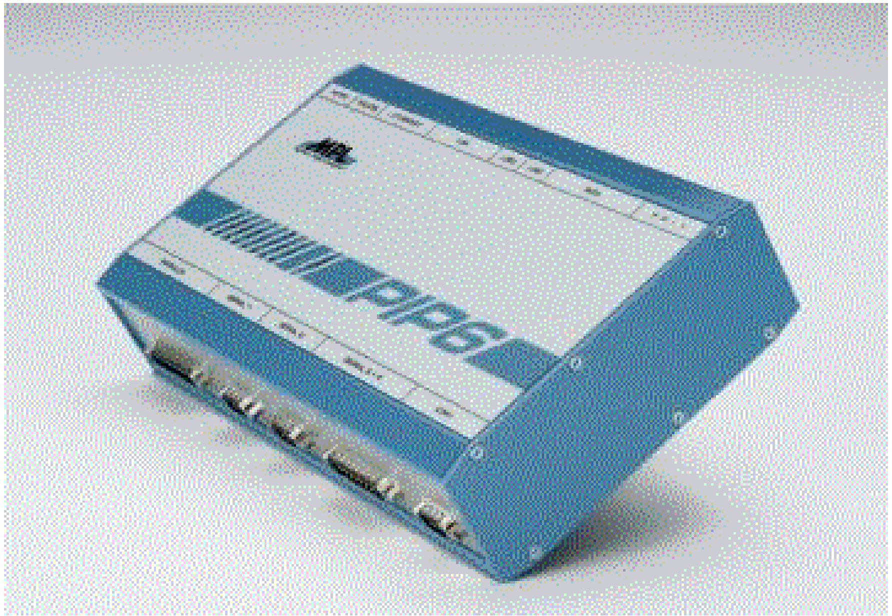


Soft-PLC ("normal" PC as PLC)

- PC as engineering workstation
- PC as human interface (Visual Basic, Intellution, Wonderware)
- PC as real-time processor
- PC assisted by a Co-Processor (ISA- or PC104 board)
- PC as field bus gateway to a distributed I/O system



Industry- PC



HMI (LCD..)
Limited modularity through mezzanine boards
(PC104, PC-Cards, IndustryPack)
Backplane-mounted versions with PCI or Compact-PCI

Competes with modular PLC
no local I/O,
fieldbus connection instead,

costs: € 2000.-

Comparison Criteria – What Matters

Brand	Siemens	Hitachi
Number of Points	1024	640
Memory	10 KB	16 KB
Programming Language	• Ladder Diagrams • Instruction List • Logic symbols • Hand-terminal	• Ladder Diagrams • Instruction List • Logic symbols • Basic • Hand-terminal
Programming Tools	Graphical (on PC)	Graphical (on PC)
Download	no	yes
Real estate per 250 I/O	2678 cm2	1000 cm2
Label surface per line/point	5.3 mm2 7 characters	6 mm2 6 characters
Network	10 Mbit/s	19.2 kbit/s
Mounting	DIN rail	cabinet

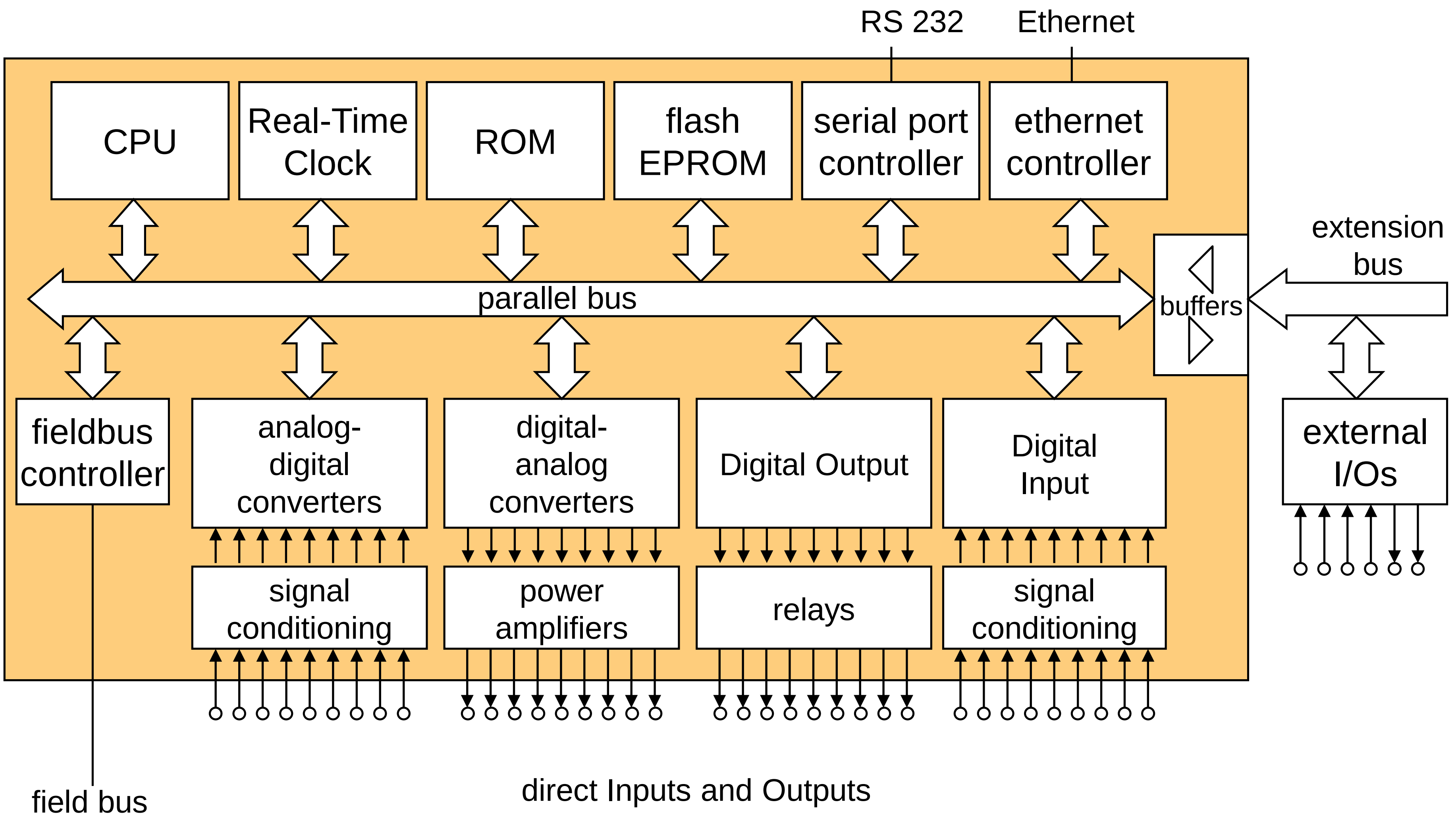
PLC Operation

- PLC operates periodically (in cycles)
- Samples signals from sensors and converts them to digital form with A/D converter
- Computes control signal and converts it to analog form for the actuators.

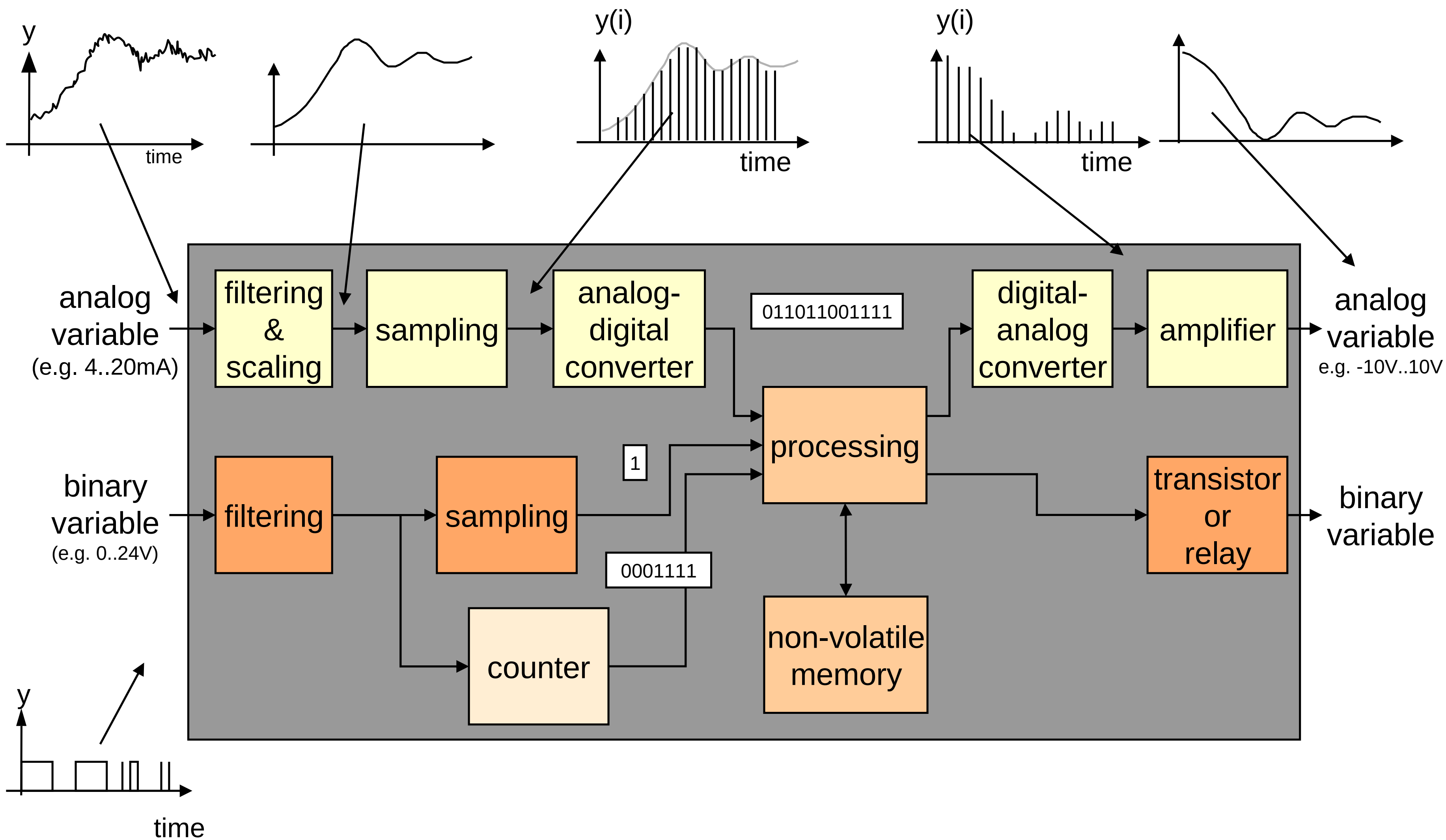
A cycle consists of:
1. Wait for clock interrupt
2. Read input from sensor
3. Compute control signal
4. Send output to the actuator
5. Update controller variables
6. Communication
7. Repeat

Waiwera Organic Winery, Distillation Plant

General PLC architecture



The signal chain within a PLC



Assessment

- What characterizes a PLC, which kinds exist and what is their application field?
- List selection criteria for PLCs
- Describe the chain of signal from the sensor to the actors in a PLC

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2.2 Basics of Control

Content

Motivation for this chapter

This is an intuitive introduction to control as a preparation for the PLC programming lab at Siemens, intended for students who did not enjoy control courses.

For a correct engineering approach, dedicated courses are recommended (e.g., by Prof. Longchamp and Prof. Bonvin).

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Content

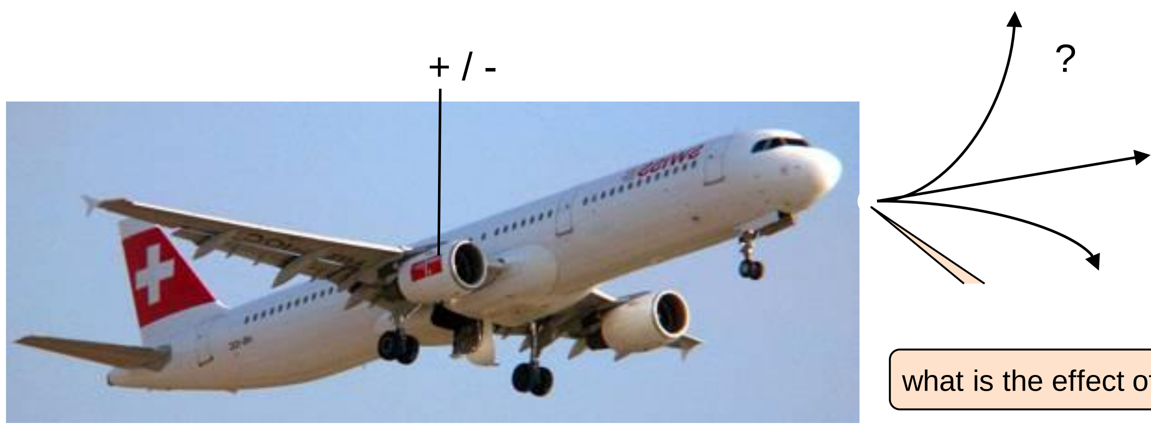
- modeling of plants
- two-point controller
- PID controller
- nested controllers

Modeling

1) Analysis of control systems
2) Define a controller that meets physical and economical requirements

The first step is to get to know the plant, i.e., express the plant's behavior in a mathematical way, generally as a system of differential equations,

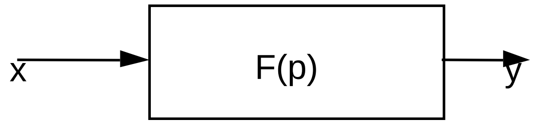
- **White box approach**: analyzing physical principles (requires that all elements are known)
- **Black box approach:** identifying the plant's parameters by analyzing its behavior (output) in response to an input change.



what is the effect of increasing thrust ?

Continuous plants

Examples: drives, ovens, chemical reactors



Continuous (analog) variables (temperature, voltage, speed,...).
Input/output relation: transfer function, described by differential equations

Conditions necessary for control:

- Reversible: output can be brought back to previous value by acting on input
- Monotone: increasing input causes output to react monotonically

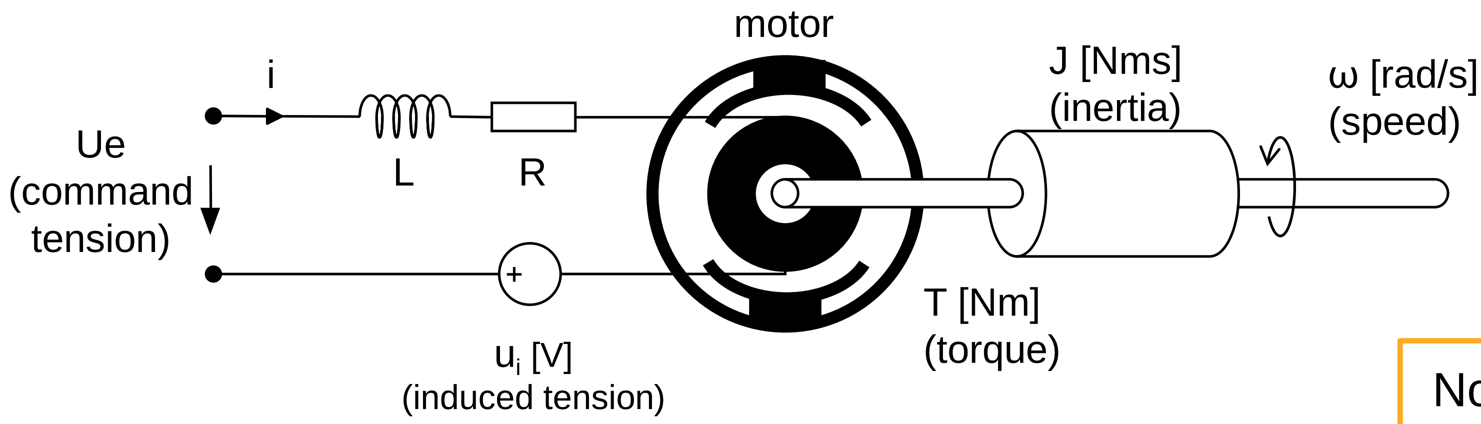
Linear system: Laplace Transformation from time to frequency domain (simpler notation and computation)

Laplace transformation: $L[f(t)] := \int_{-0}^{\infty} f(t)e^{-st}dt$

$$f(t) \Rightarrow G(s),\ where\ s = \sigma + j\omega.$$

Main goal: maintain the state on given level or trajectory

Example linear model: electrical motor with permanent magnet



Not for exam, illustration only

$$Ue = R\,i + L\frac{di}{dt} + u_i$$

$$u_i = K\,\omega$$

$$T = K\,i$$

$$\frac{d\omega}{dt} = \frac{T}{J}$$

⇒

$$\frac{di}{dt} = \frac{1}{L}(Ue - K\,\omega - R\,i)$$

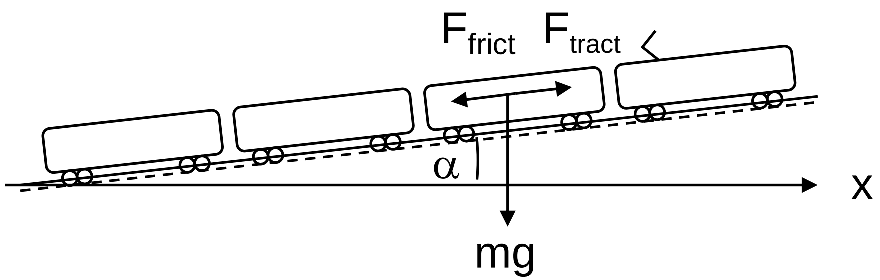
$$\frac{d\omega}{dt} = \frac{K}{J}\,i$$

$$\frac{\omega}{Ue} = \frac{K}{s^2 (LJ) + s\,(RJ) + K^2}$$

Laplace - transfer, since the plant is linear

Example of non-linear model: train

Obtain the relation between applied motor force (current) and the position of a train.



$$\begin{cases} \dfrac{dx}{dt} = v \\ \dfrac{dv}{dt} = \dfrac{1}{m\rho}\left(F_{tract} - mg\sin(\alpha) - m\dfrac{K_c}{radius} - C_x v^2 - C_f v\right) \end{cases}$$

motor force

mass of the train plus contribution of rotating parts (wheels and rotors)

slope

curve friction

air friction

mechanical friction

Not for exam, illustration only

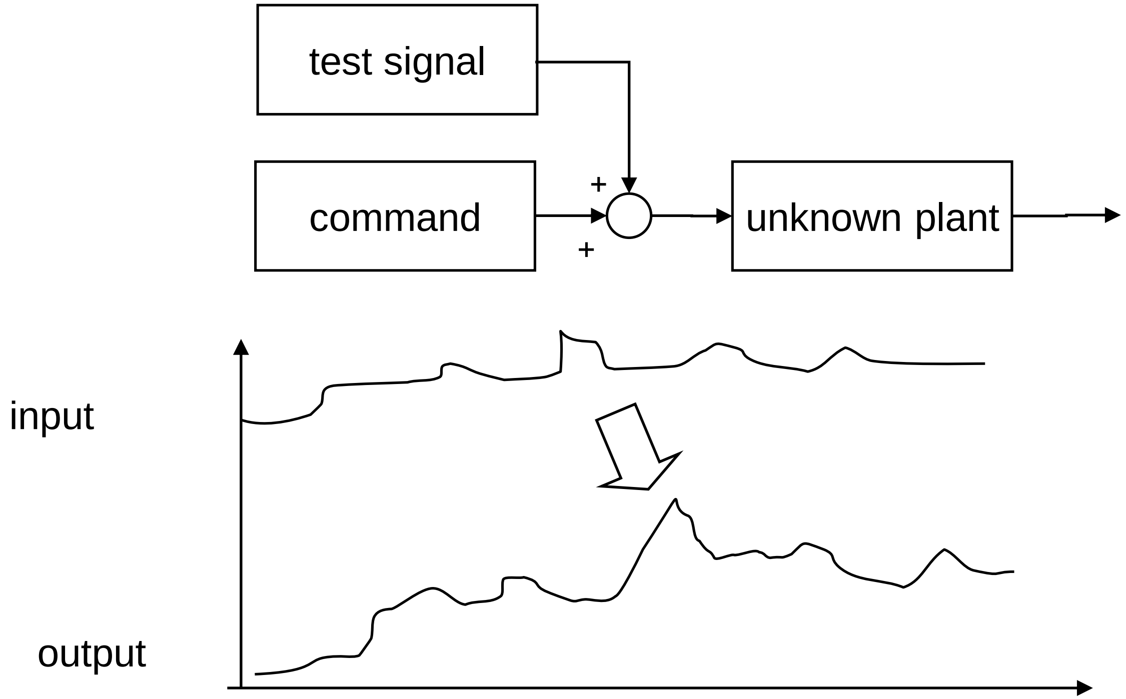
Plant Identification

Once model is approximately known, parameters must be determined by measurements.

Classical methods:

- Response to a pulse at input
- Response to calibrated noise at input (in case the command signal varies little)

Signal correlation then yields the parameters.



Control Mechanism

When plant is known, a controller can be designed.

In practice, plants' parameters vary (e.g., # passengers in train), and plant is subject to disturbances (wind, slope)

Controller

- needs to measure through sensors the state of the plant and if possible the disturbances.
- follows certain quality laws to stabilize the output within useful time, not overshoot, minimize energy consumption, etc…..

Types of Control Mechanisms: Definitions from IEC

351-47-01 closed-loop control (feedback control)

process whereby one variable quantity, namely the controlled variable is continuously or sequentially measured**,** compared with another variable quantity, namely the reference variable, and influenced in such a manner as to adjust to the reference variable

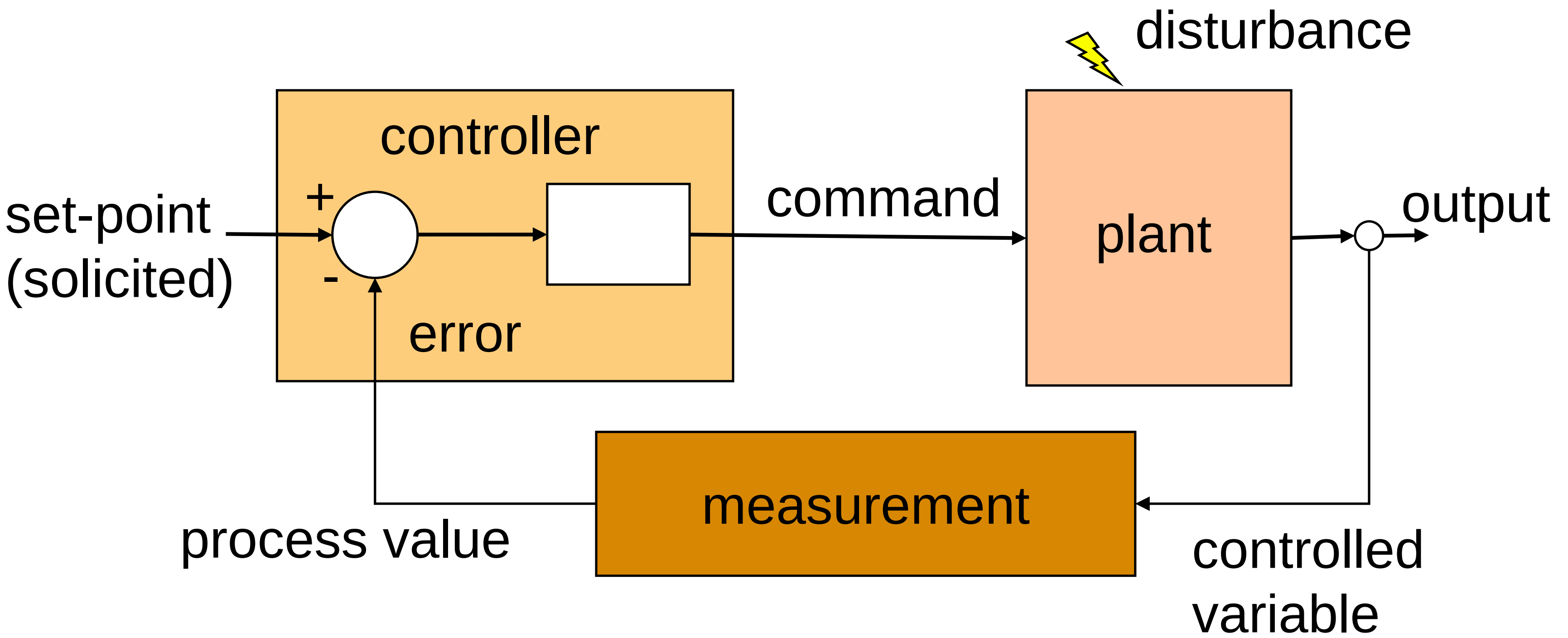
Closed action path in which the controlled variable continuously or sequentially influences itself

351-47-02 open-loop control

process in a system whereby one or more variable quantities as input variables influence other variable quantities as output variables in accordance with the proper laws of the system

Open action path or a closed action path in which the output variables being influenced by the input variables are not continuously or sequentially influencing themselves and not by the same input variables

Controller loop (boucle de régulation, Regelschleife)



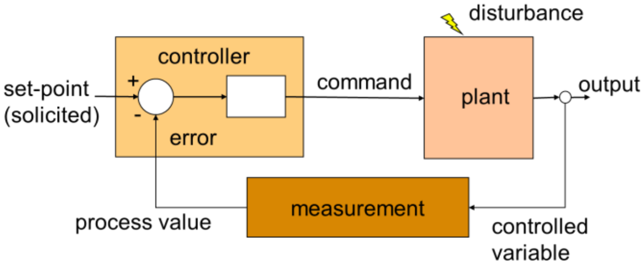
Implemented by mechanical or electrical elements, computers,...

Controlled variable can not always be measured directly.

Example Cruise Control

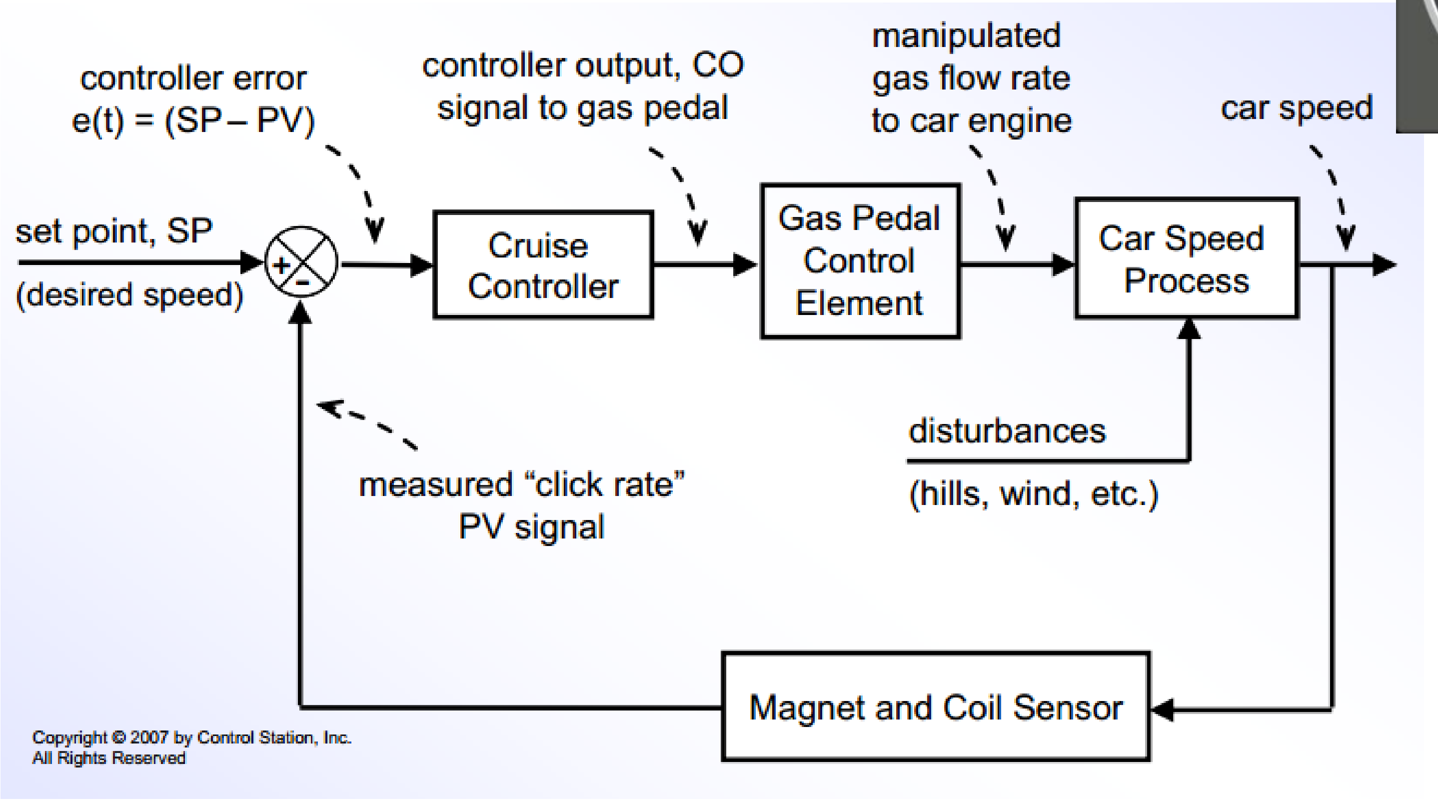
- Control Objective:
  maintain car velocity
- Measured Process Variable (PV):
- Manipulated Variable:
- Controller Output (CO):
- Set point (SP):
- Disturbances (D):

Source: OCAL, clker.com



Source: http://apmonitor.com/che436/uploads/Main/Lecture3_notes.pdf

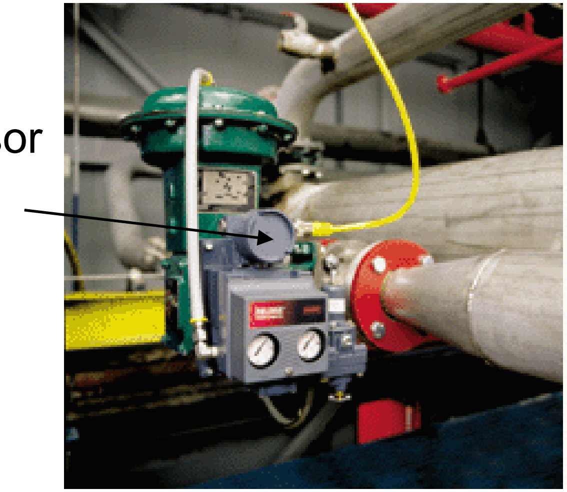
Example Cruise Control



Source: http://apmonitor.com/che436/uploads/Main/Lecture3_notes.pdf

Where is that controller located ?

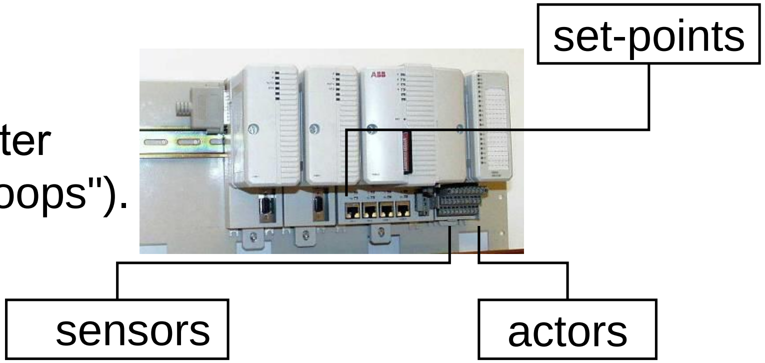
- directly in the sensor or in the actuator (analog PIDs)



- high-end: in a set of possibly redundant controllers (here: turbine control)

- as a separate device (analog PIDs) (some times combined with a recorder)

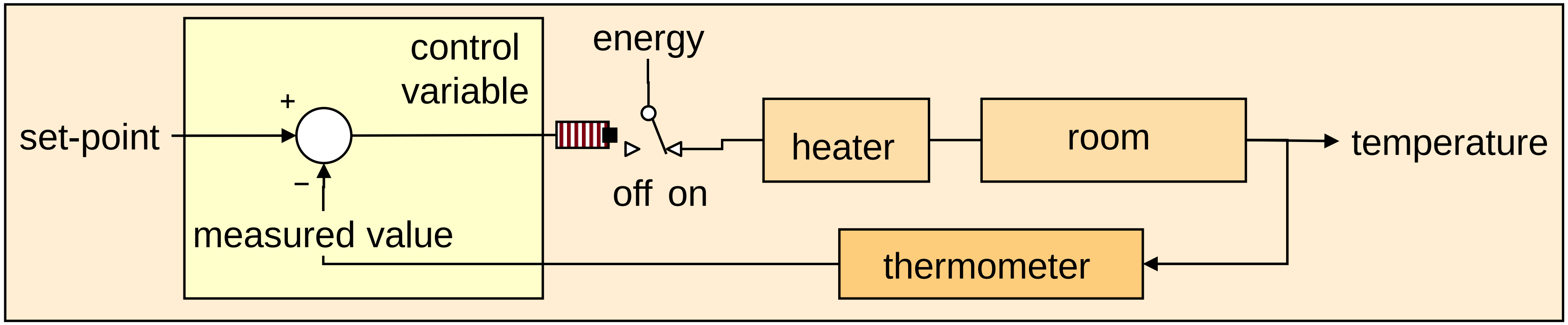
- as an algorithm in a computer (that can handle numerous "loops").



Content

Two-point controller: principle

The two-point controller (or bang-bang controller, regulator, *Zweipunktregler*, Régulateur tout ou rien) has a binary output: on or off (example: air conditioning)



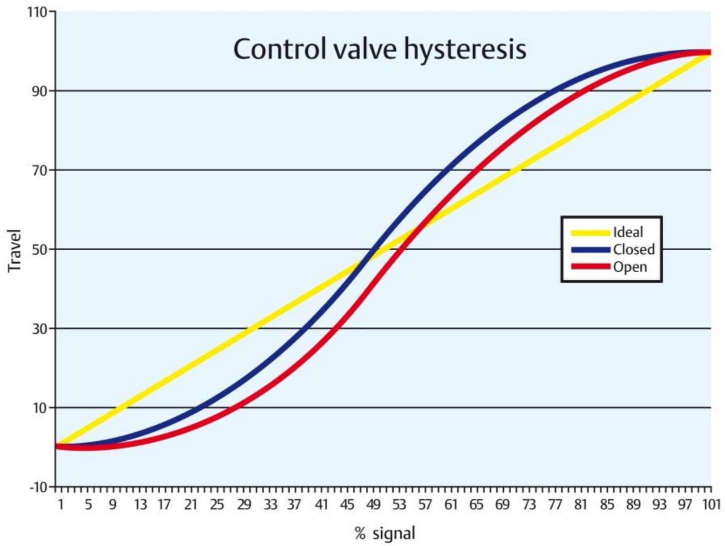
Honeywell T-86 “Round” Thermostat (1953)

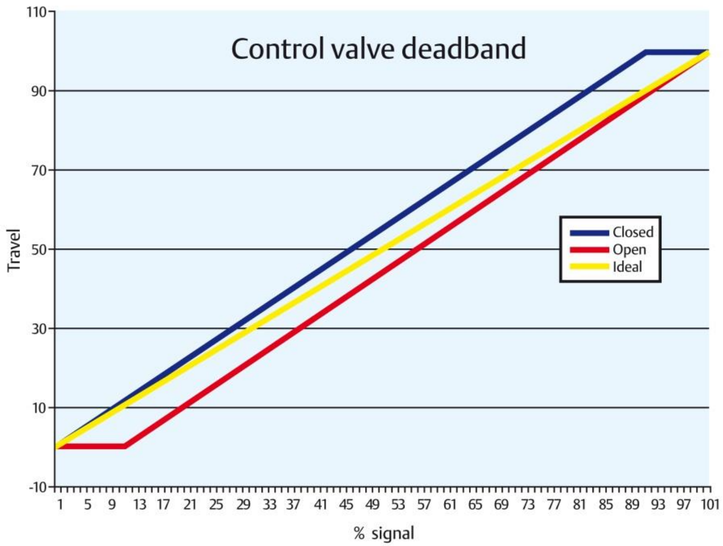
Nest 2nd Gen Learning Thermostat (2014)

Hysteresis and Deadband of a Valve

Hysteresis: difference between the valve position on the up-stroke and its position on the down-stroke at any given input signal (static friction)

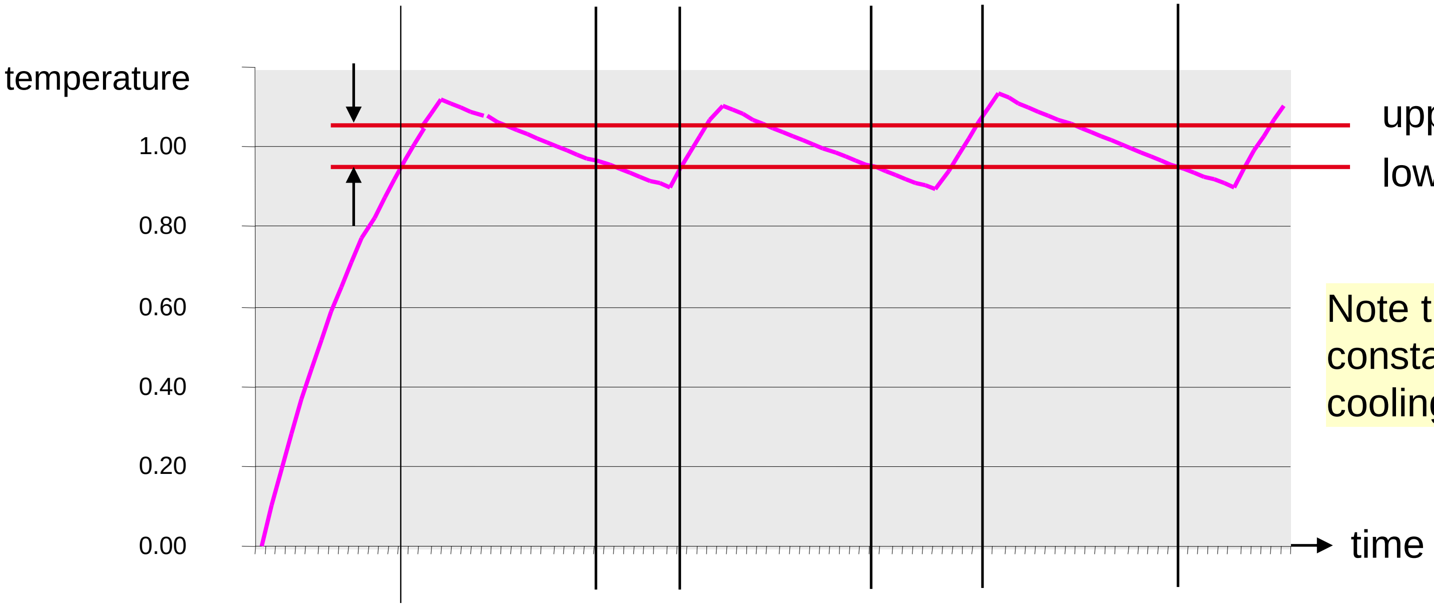
Deadband: no movement, generally occurs when the valve changes direction.





Source: http://www.processindustryforum.com/solutions/valve-terminology-basic-understanding-of-key-concepts

Two-point controller: Hysteresis / Deadband

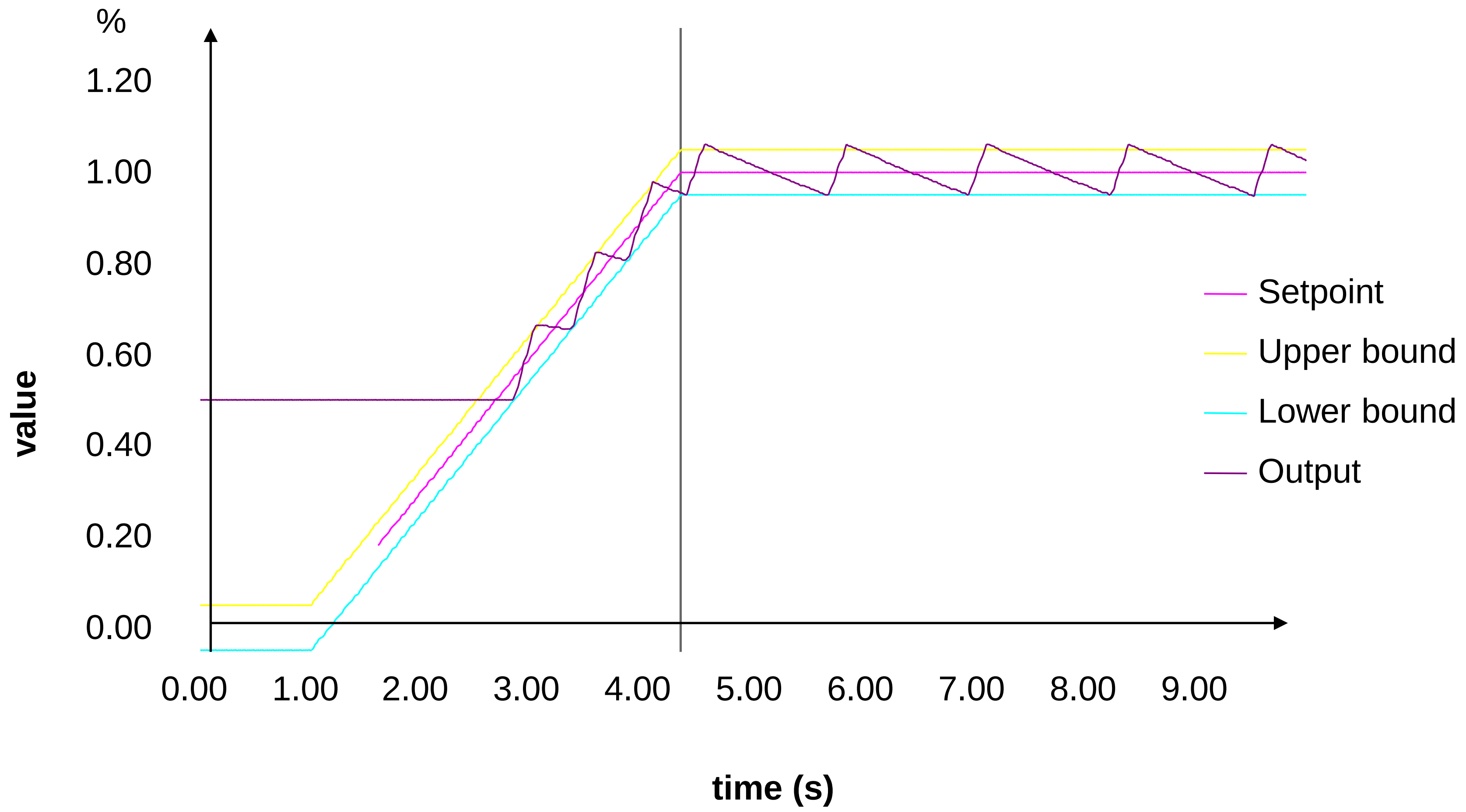


Note the different time constants for heating and cooling: non-linear system

If the process is not slow enough, hysteresis and deadband are included in switch point calculation to limit switching frequency and avoid wearing off the contactor.

(thermal processes are normally so inertial that this is usually not needed)

Two-point controller: Input variable as ramp



Content

2.1 PLCs (controllers)

2.2 Basics of control

- Modeling of plants
- Two-point controller
- **PID controller**
- Nested controllers

2.3 Programming PLCs

Proportional-Integral-Derivative (PID) Controller

Generic and widely used control loop feedback mechanism

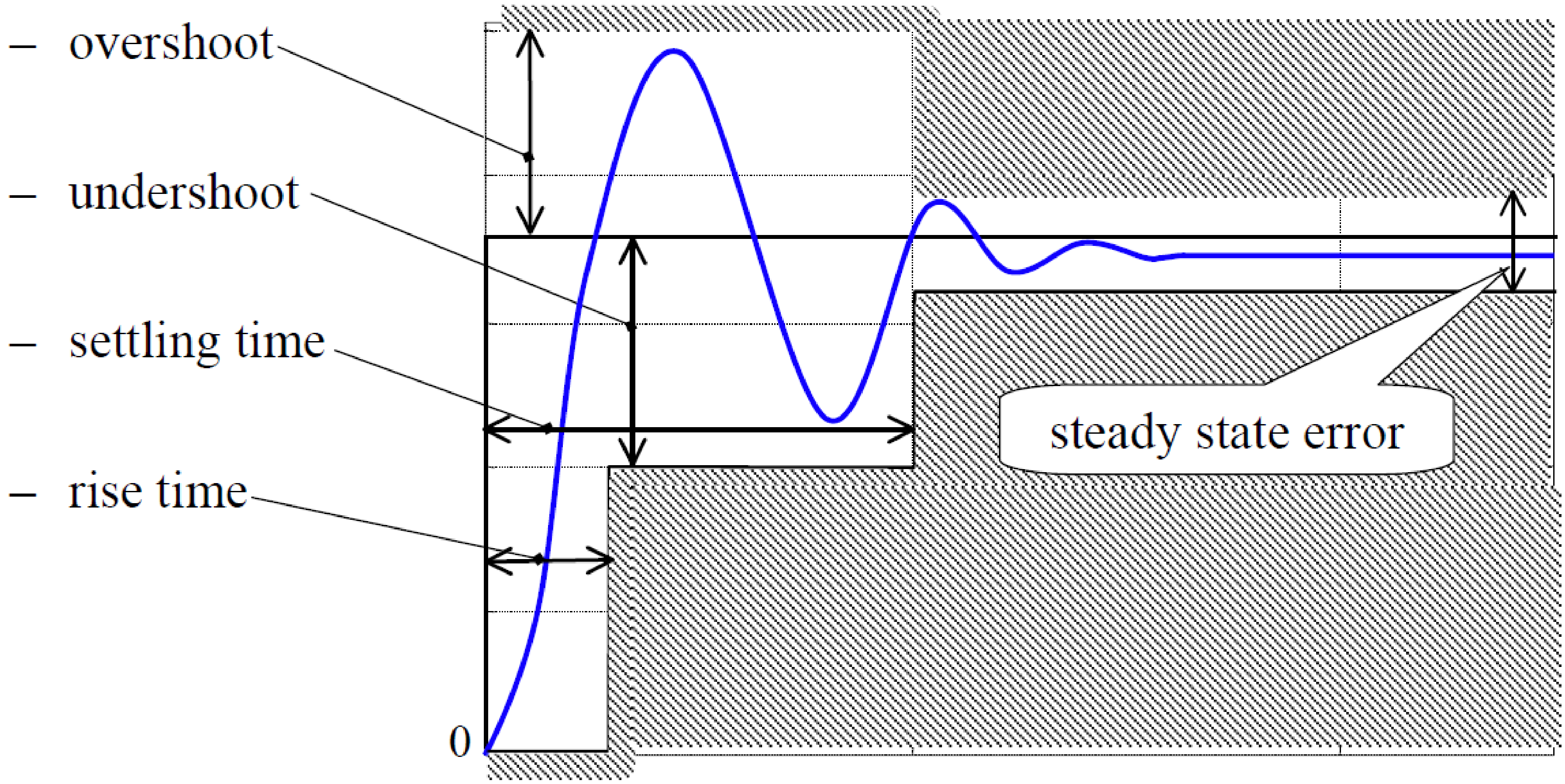
Mode of operation:

1. calculate error *e(t)*, the difference between measured PV and SP.
2. try to minimize error by adjusting the process control output *m*.

$$m(t) = u_b + K_p\left(e(t) + \frac{1}{T_i}\int_{t0}^{t} e(\tau)d\tau) + T_d\,\frac{de(t)}{dt} \right)$$

K_p, T_i, T_d tuning parameters

Step response



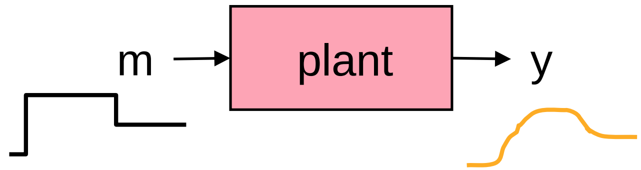
Source: http://www.stanford.edu/class/archive/ee/ee392m/ee392m.1034/Lecture6_Analysis.pdf

Plant model example

The following examples use a plant modeled by a 2nd order differential equation:

$$y + y'T_1 + y''T_2 = m$$

differential equation



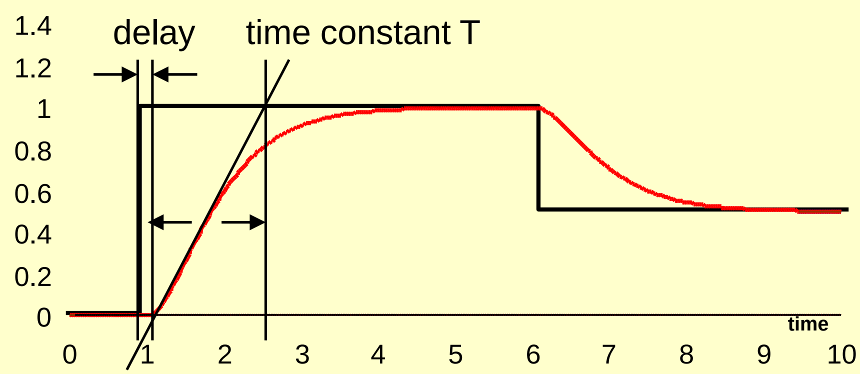
Temporal response

$$\frac{y}{m} = \frac{1}{1 + sT_1 + s^2 T_2}$$

Laplace transfer function
(since system is linear)

Typical transfer function of a plant with slow response, but without dead time
(such a plant can also be approximated by a first-order low-pass and a dead time).

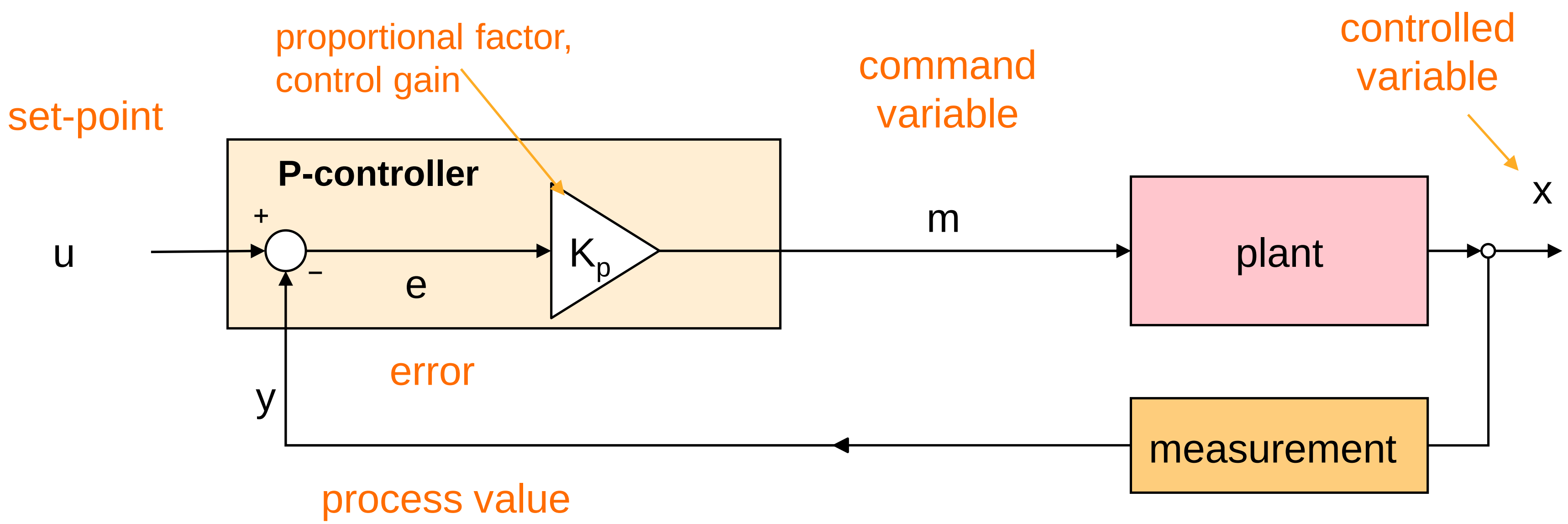
step response



d ~ 0.2, T= 1.5s

In the examples:
$T_1 = 1$ s
$T_2 = 0.25$ s^2

P-controller: simplest continuous regulator



the P-controller simply amplifies the error to obtain the command variable

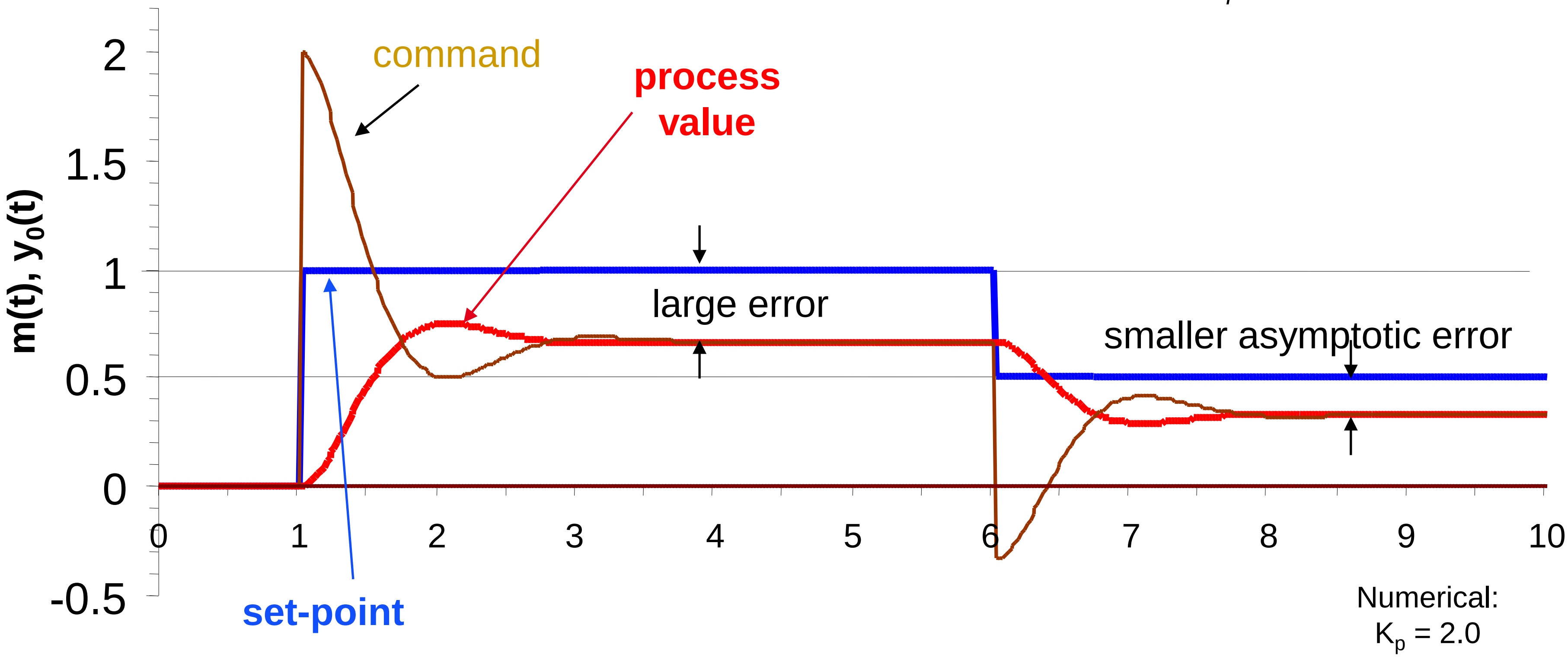
$$m(t) = u_b + K_p \cdot e(t) = K_p \cdot (u(t) - y(t))$$

works, but if plant has a proportional behavior, an error always remains

P-Controller: Step response

$$m(t) = u_b + K_p \cdot e(t) = K_p \cdot (u(t) - y(t))$$

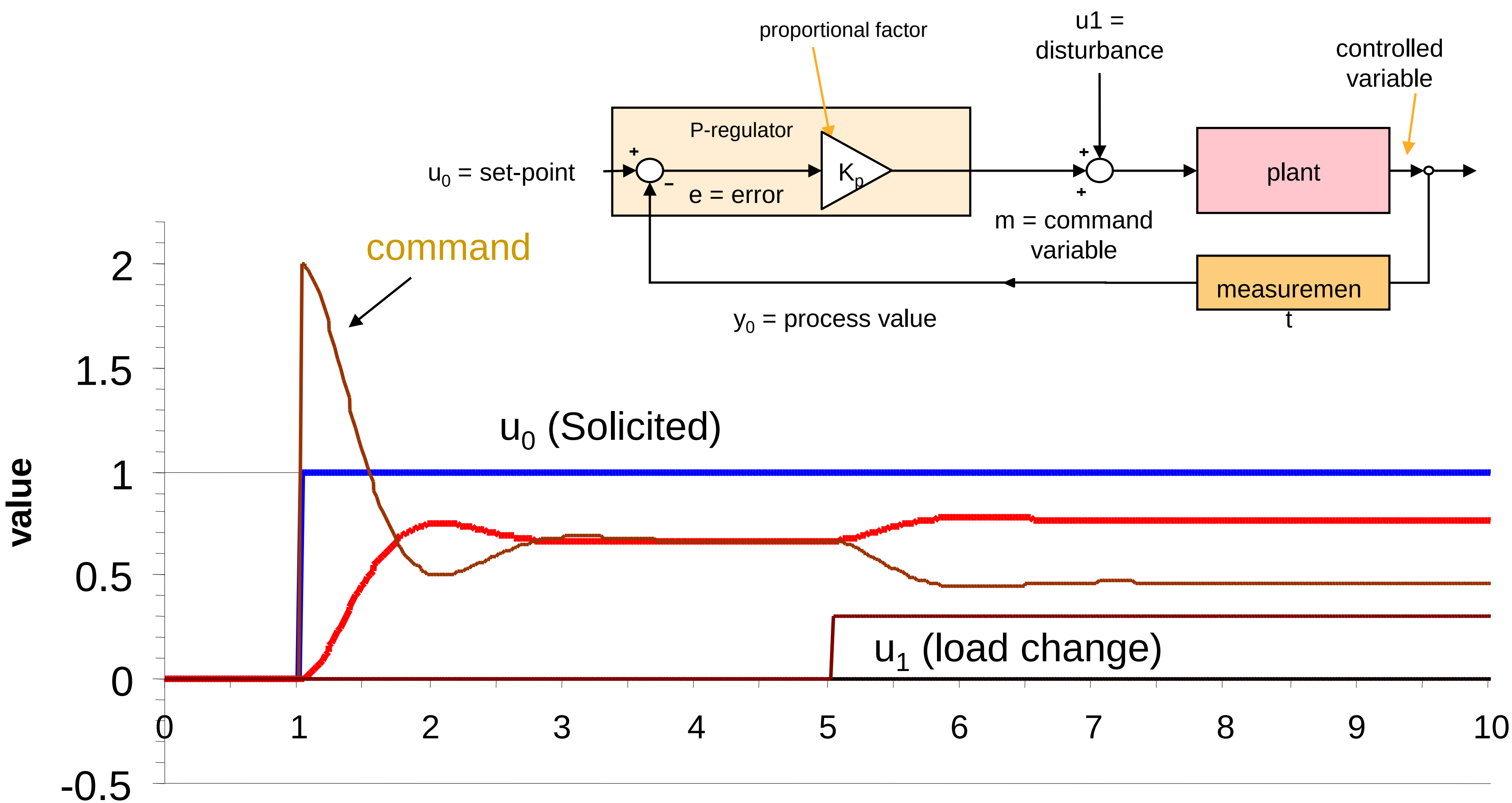
$$u_b = 0; K_p = 2$$



Numerical: $K_p = 2.0$

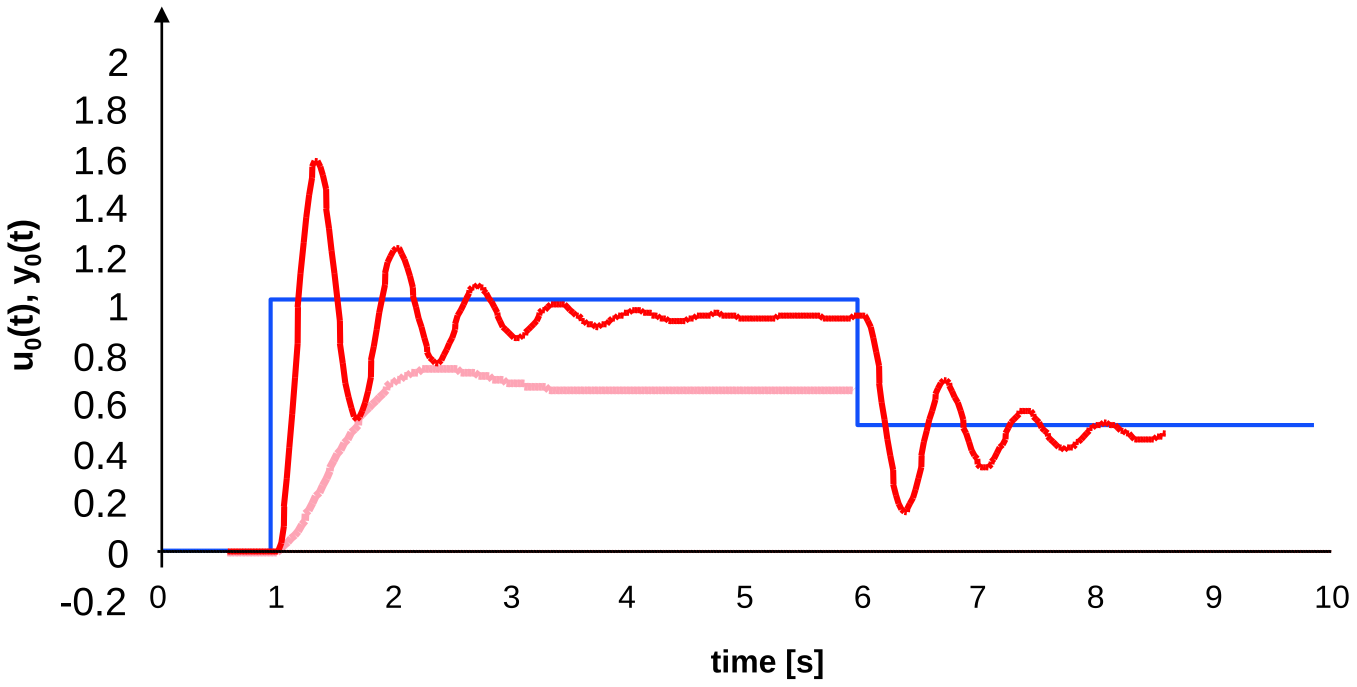
The larger the set-point, the greater the error.

P-Controller: Effect of Load change



Not only a set-point change, but a load change causes the error to increase or decrease.
(A load change, modeled by disturbance u_1, is equivalent to a set-point change)

P-Controller: Increasing the proportional factor



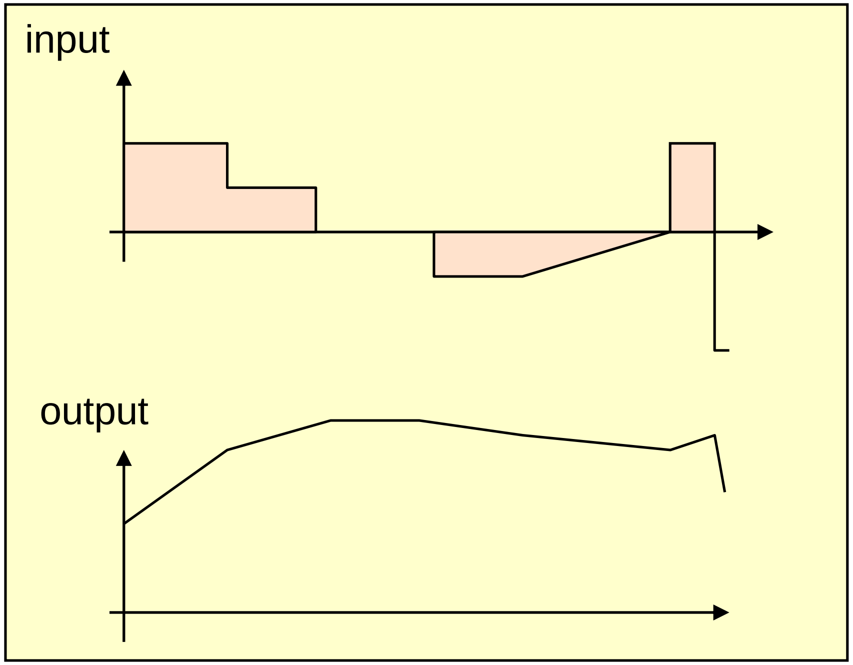
increasing the proportional factor reduces the error, but the system tends to oscillate

PI-Controller (Proportional Integrator)

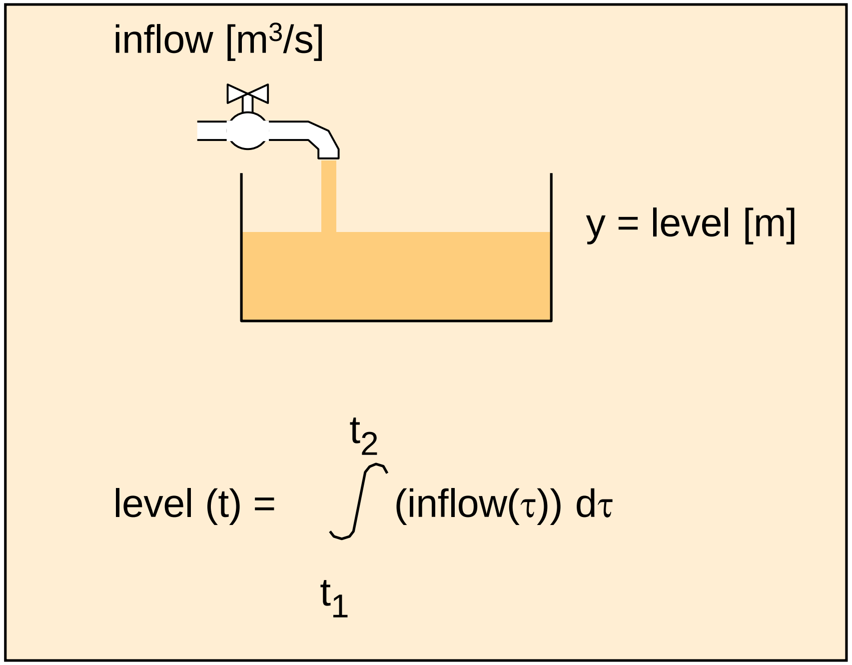
Time domain $$m = K_p(e(t) + \frac{1}{T_i}\int_{t0}^{t} e(\tau)d\tau)$$

T_i = reset time

Laplace domain $$\tilde{m} = K_P(1 + \frac{1}{sT_i})\tilde{e}$$

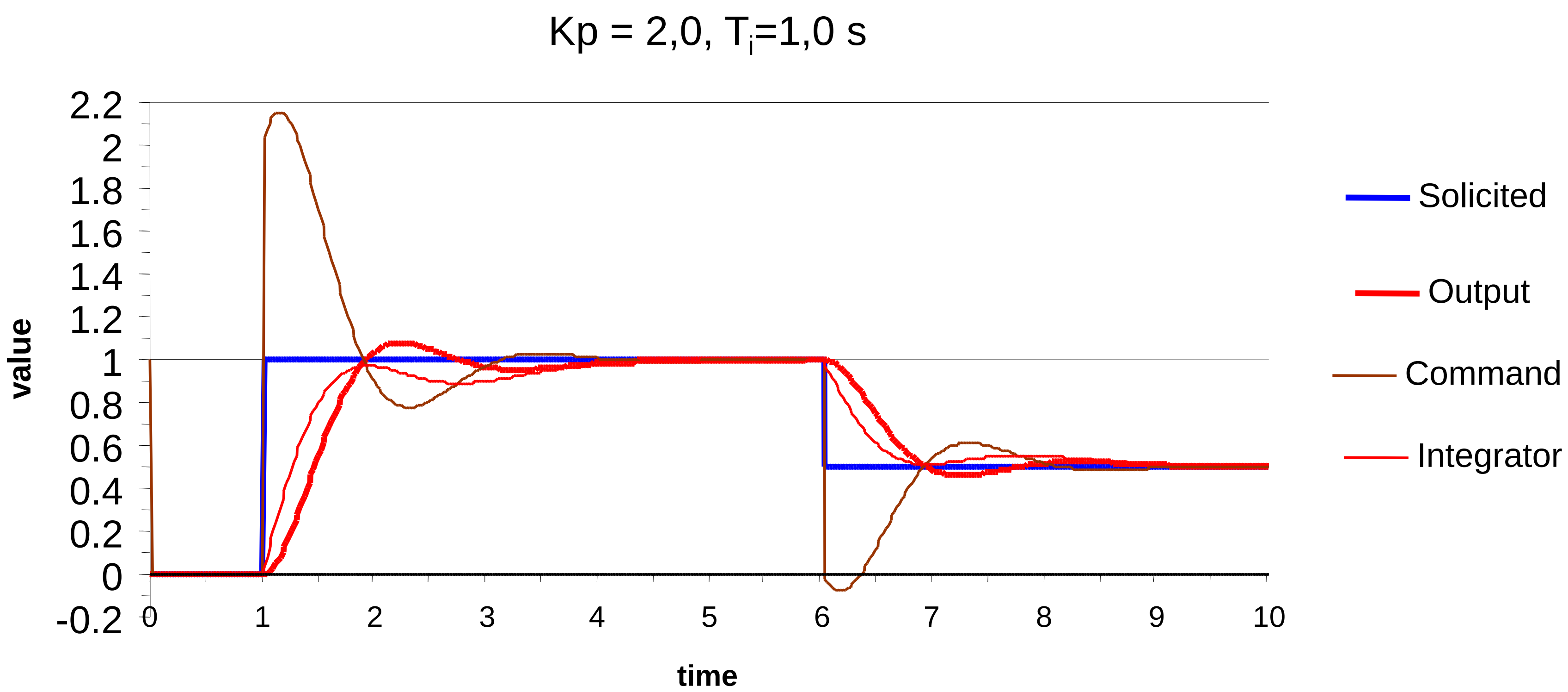


Time response of an integrator



Example of an integration process

PI-Controller: response to set-point change



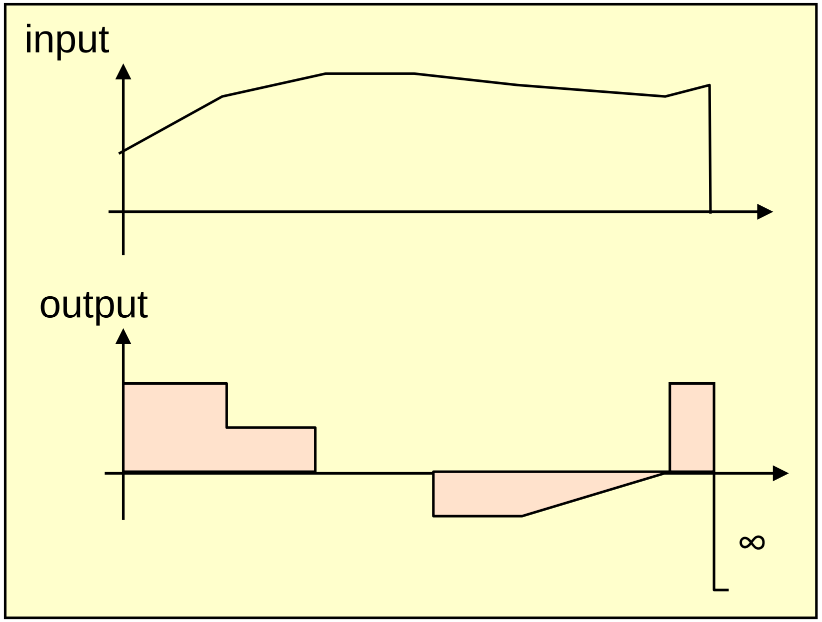
The integral factor reduced the asymptotical error to zero, but slows down the response (if K_p is increased to make it faster, the system becomes unstable)

PD-Controller: Proportional Differentiator

Time domain $$m(t) = K_p \left(e(t) + T_d \frac{de(t)}{dt} \right)$$

T_d = derivative time

Laplace domain $$\tilde{m}(s) = K_p (1 + T_d s) \tilde{e}(s)$$

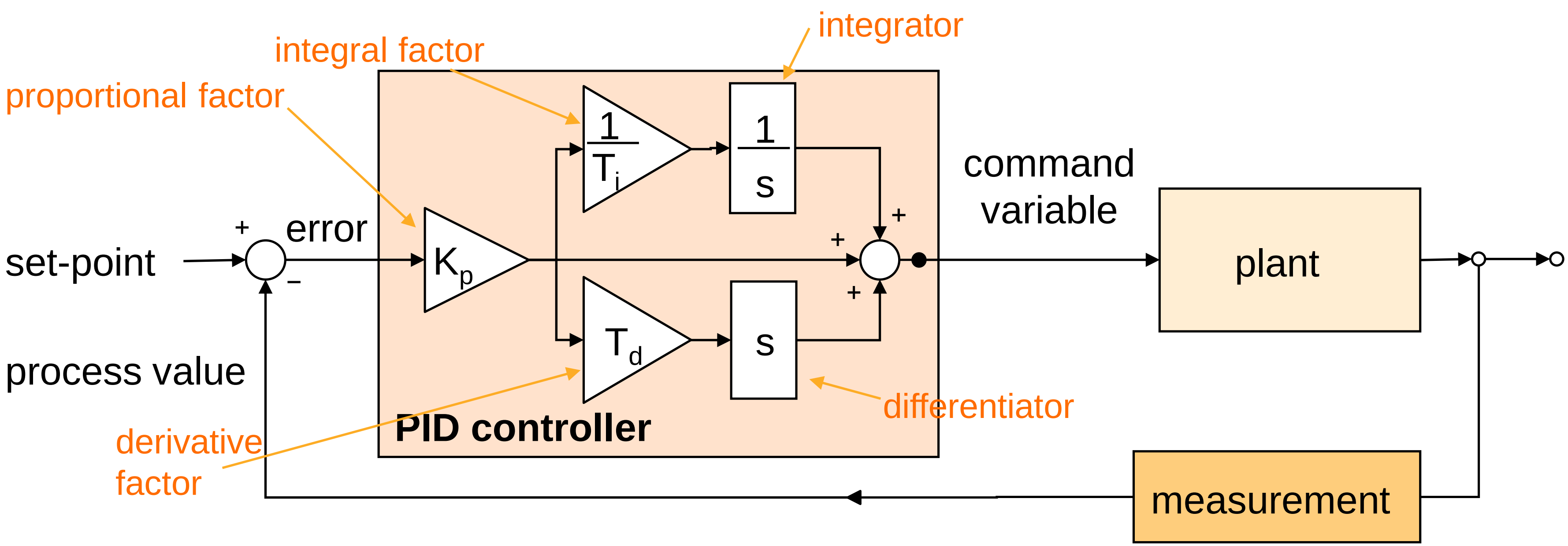


temporal response:

A perfect differentiator does not exist.
Differentiators increase noise.
Differentiators are approximated by feed-back integrators (filtered differentiator):

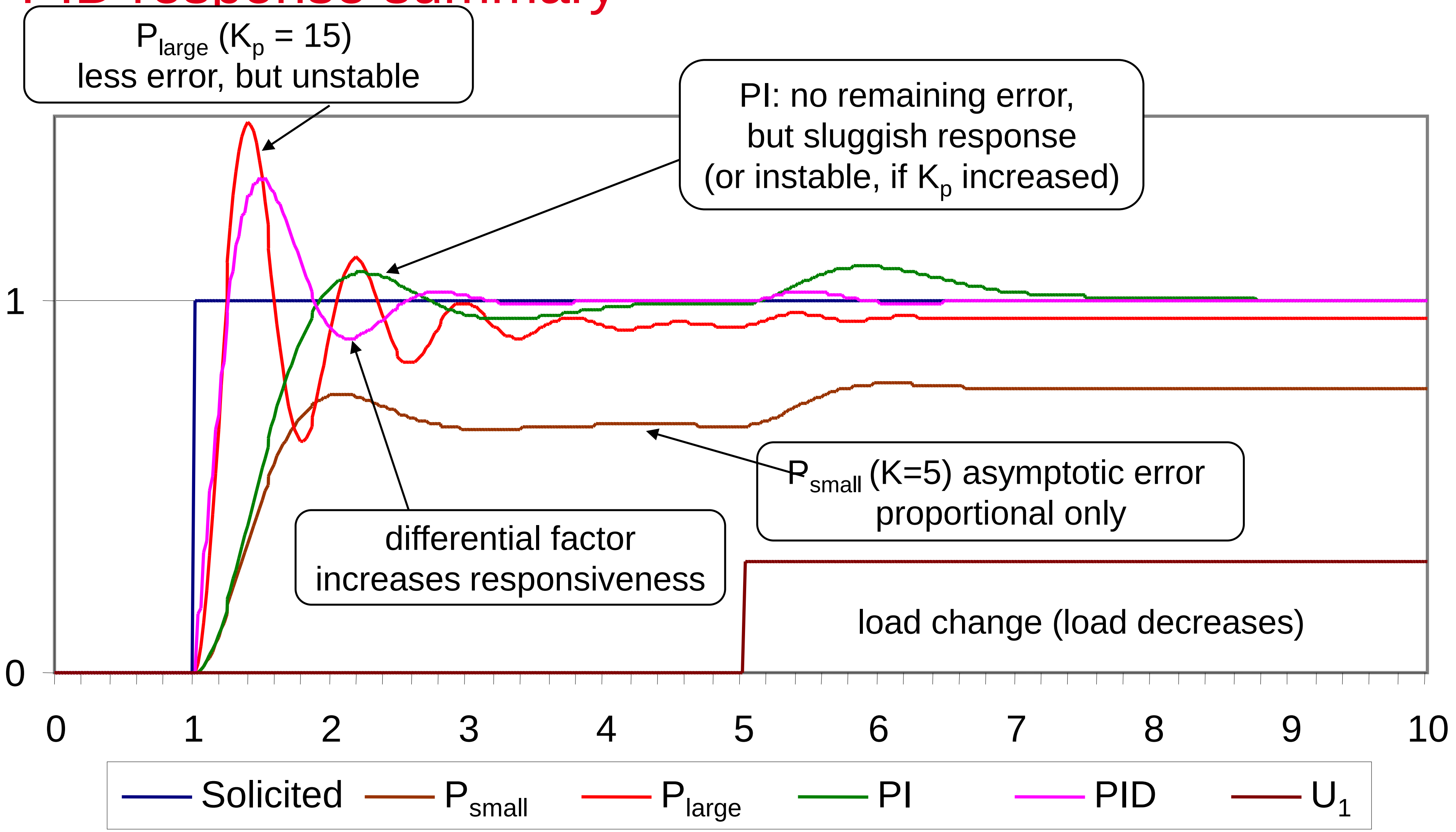
Instead of differentiating, one can use an already available variable:
e.g. the speed for position control

PID-Controller



- K_p generates output proportional to error, requires non-zero error
- Increasing K_p decreases the error, but may lead to instability
- Increasing T_i can make system slower
- T_d speeds up response by reacting to error change proportionally to slope of change.

PID response summary

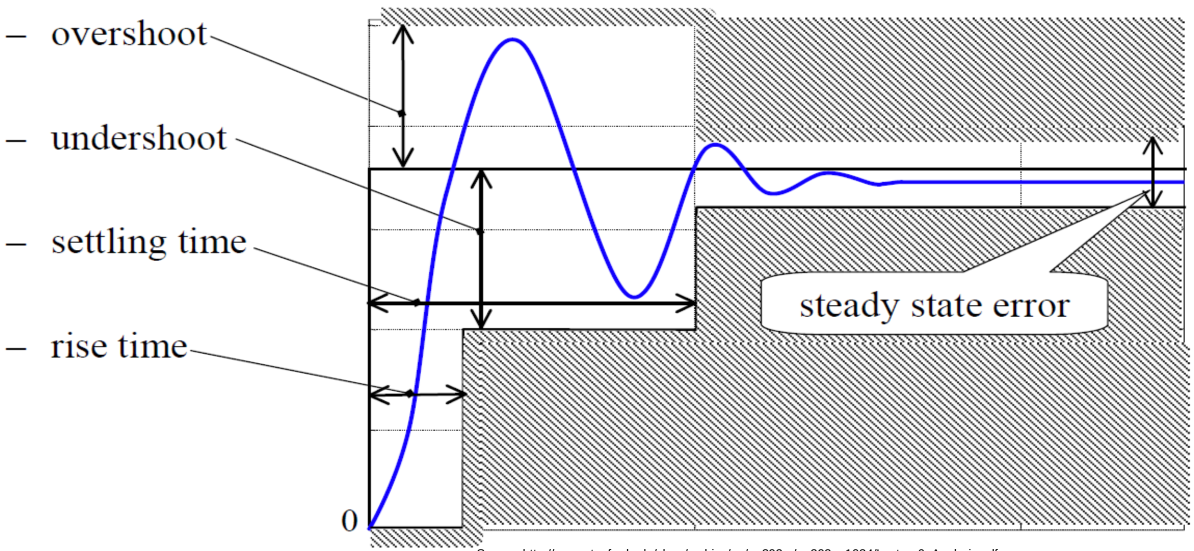


Play with Matlab: **http://ctms.engin.umich.edu/CTMS/index.php?example=Introduction&section=ControlPID**
or control.xls

PID-Controller: empirical settings

increasing	Rise time	Overshoot	Settling time	Steady-State
Kp	Decrease	Increase	Small Change	Decrease
Ti	Decrease	Increase	Increase	Eliminate
Td	Small Change	Decrease	Decrease	Small Change

See examples on http://en.wikipedia.org/wiki/PID_controller



Source: http://www.stanford.edu/class/archive/ee/ee392m/ee392m.1034/Lecture6_Analysis.pdf

Extract from a controller's manual: it's empirical !

Optimization according to Ziegler-Nichols:
Assuming that the process is stable at the operating value:

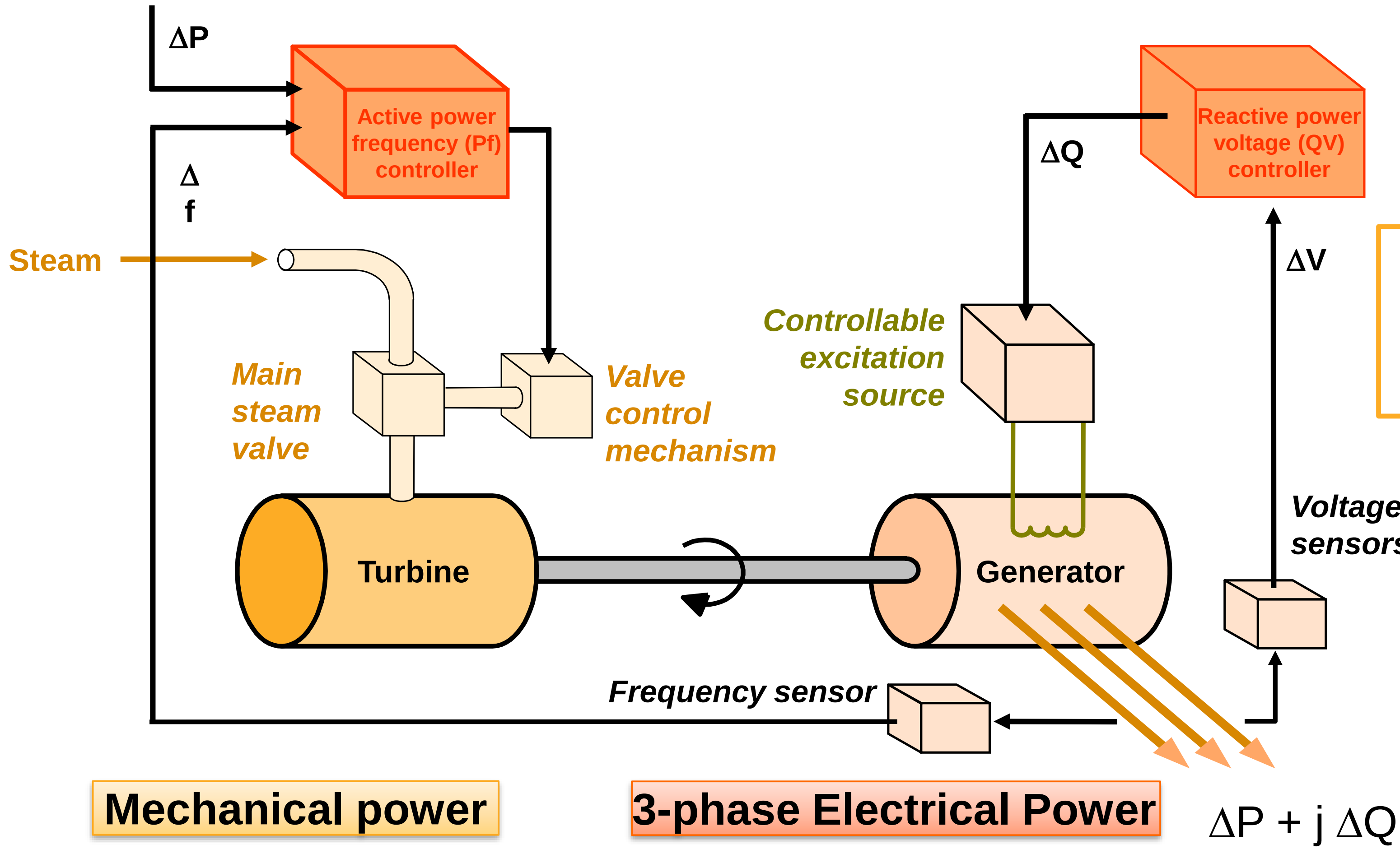
1. Set the Parameters 'Ti' und 'Td' to OFF.
2. Actual value differs now from solicited value by proportional factor.
3. As soon as value stabilizes, reduce proportional band 'Kp', until temperature starts to oscillate=> oscillation period „T".
4. Slowly increase proportional band Kp until value just stops oscillating => band value 'B'.
5. Set values of Kp, Ti and Td according to table

Control Type	Kp	Ti	Td
P	0.5 B	-	-
PI	0.45 B	T /1.2	-
PD	0.8 B	-	T / 8

But what do you do if this method does not work ?
How do you know that this plant can be controlled by a PID controller? (many cannot)
How do you prevent overshoot ? (this method does not)

Today's PIDs often provide autotuning.

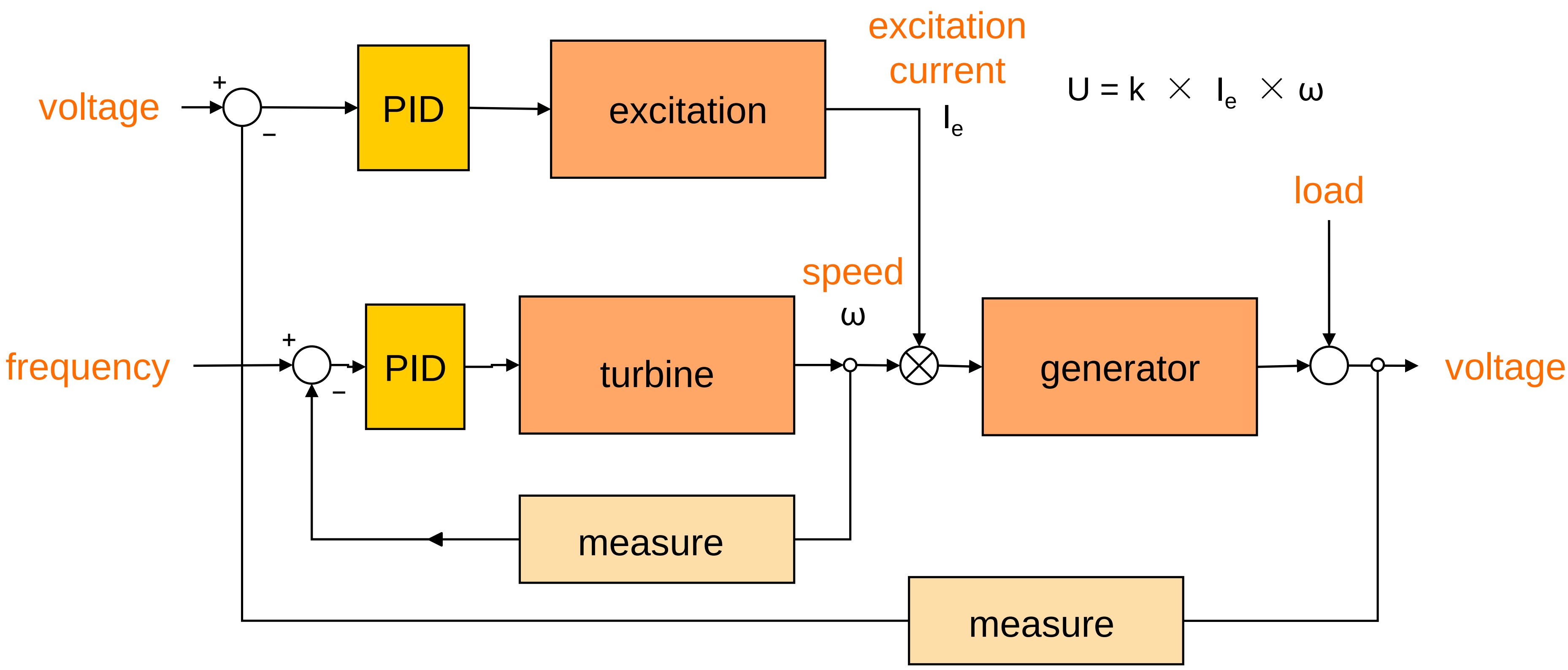
Several controllers act together: Electricity Generator



Not for exam, illustration only

Generator Regulator structure

Not for exam, illustration only



Content

2.1 PLCs (controllers)

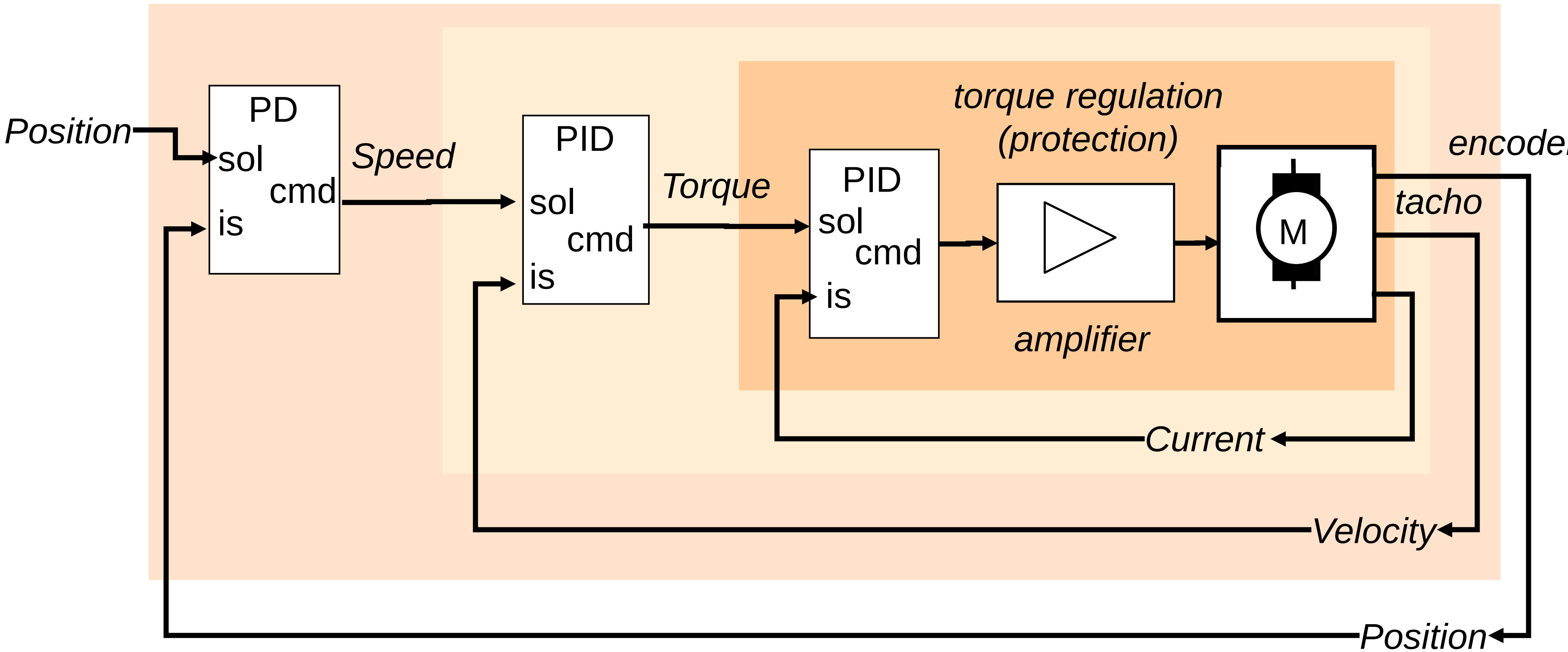
2.2 Basics of control

- Modeling of plants
- Two-point controller
- PID controller
- **Nested controllers**

2.3 Programming PLCs

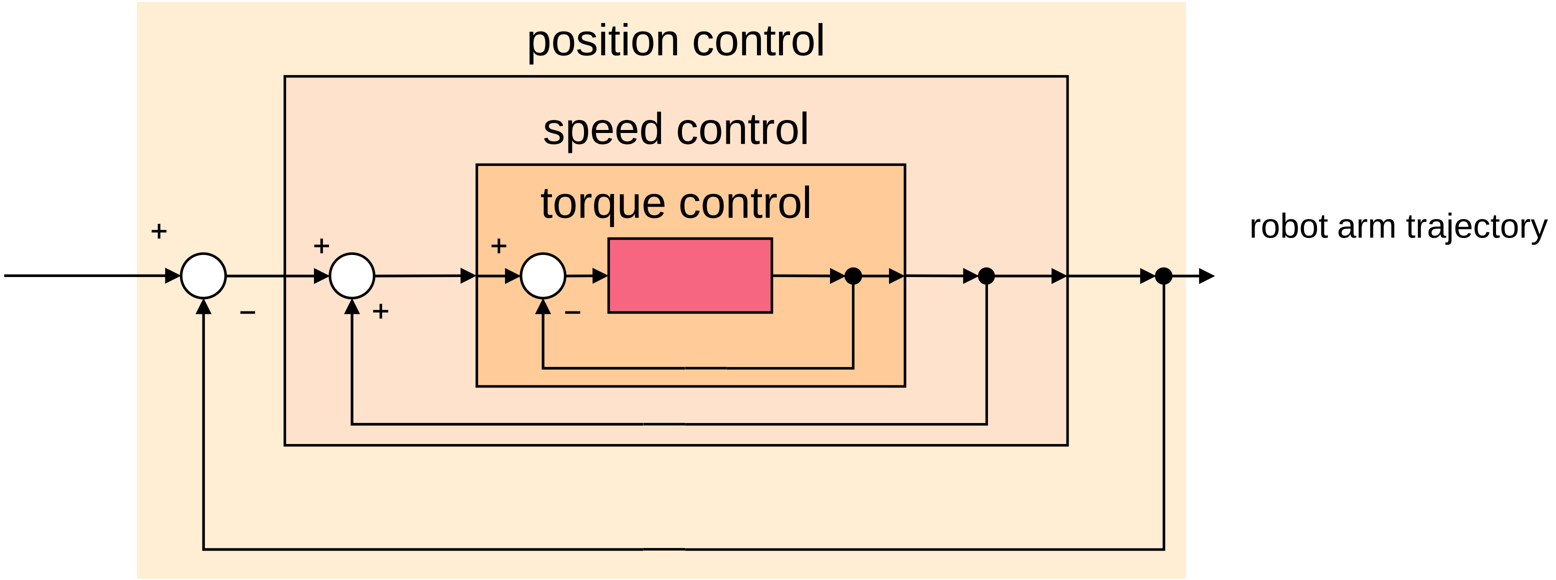
Nested control of a continuous plant - example

Example: position control of a rotating shaft



Nesting regulators allow to maintain the output variable at a determined value while not exceeding the current or speed limitations

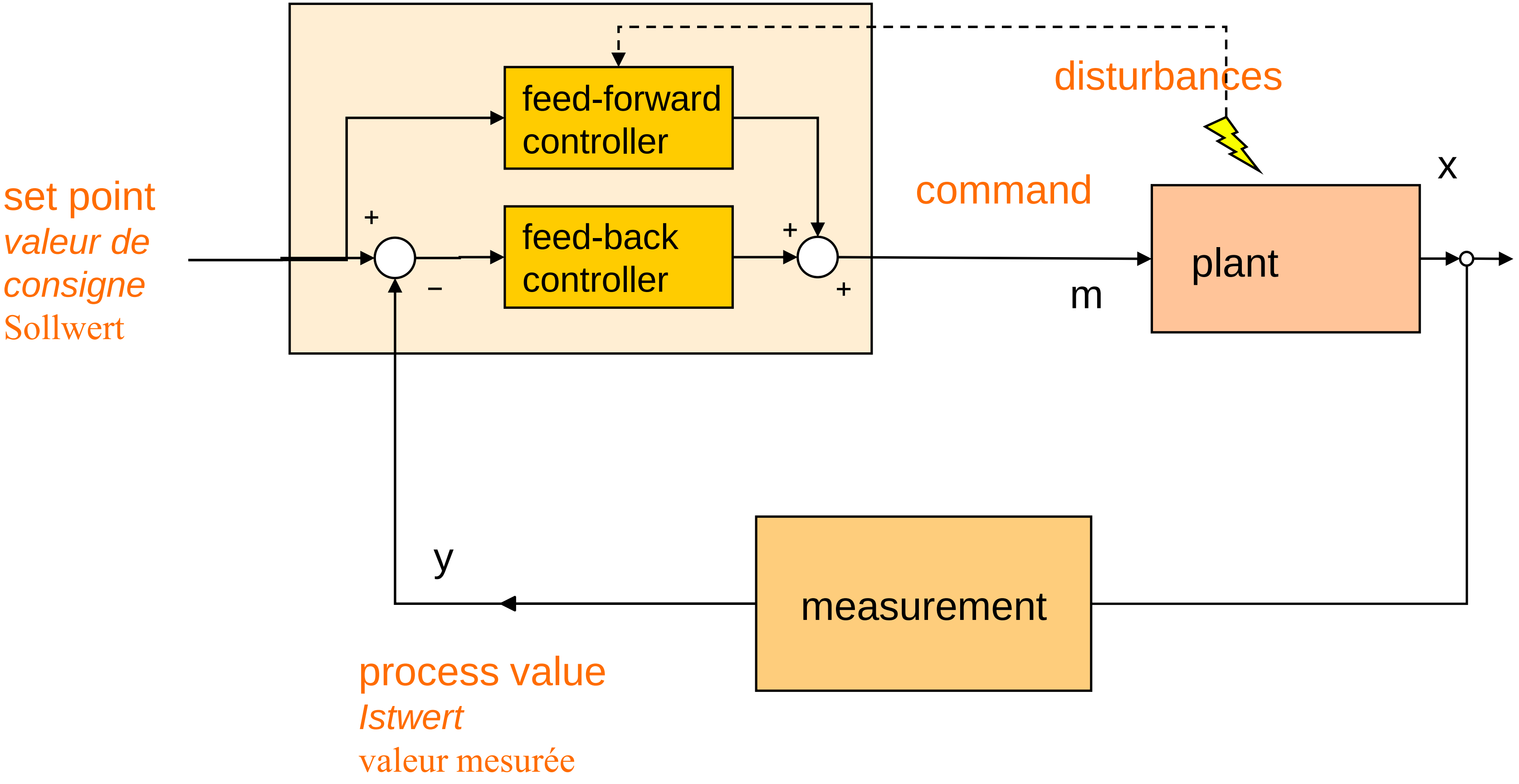
Nested loops and time response



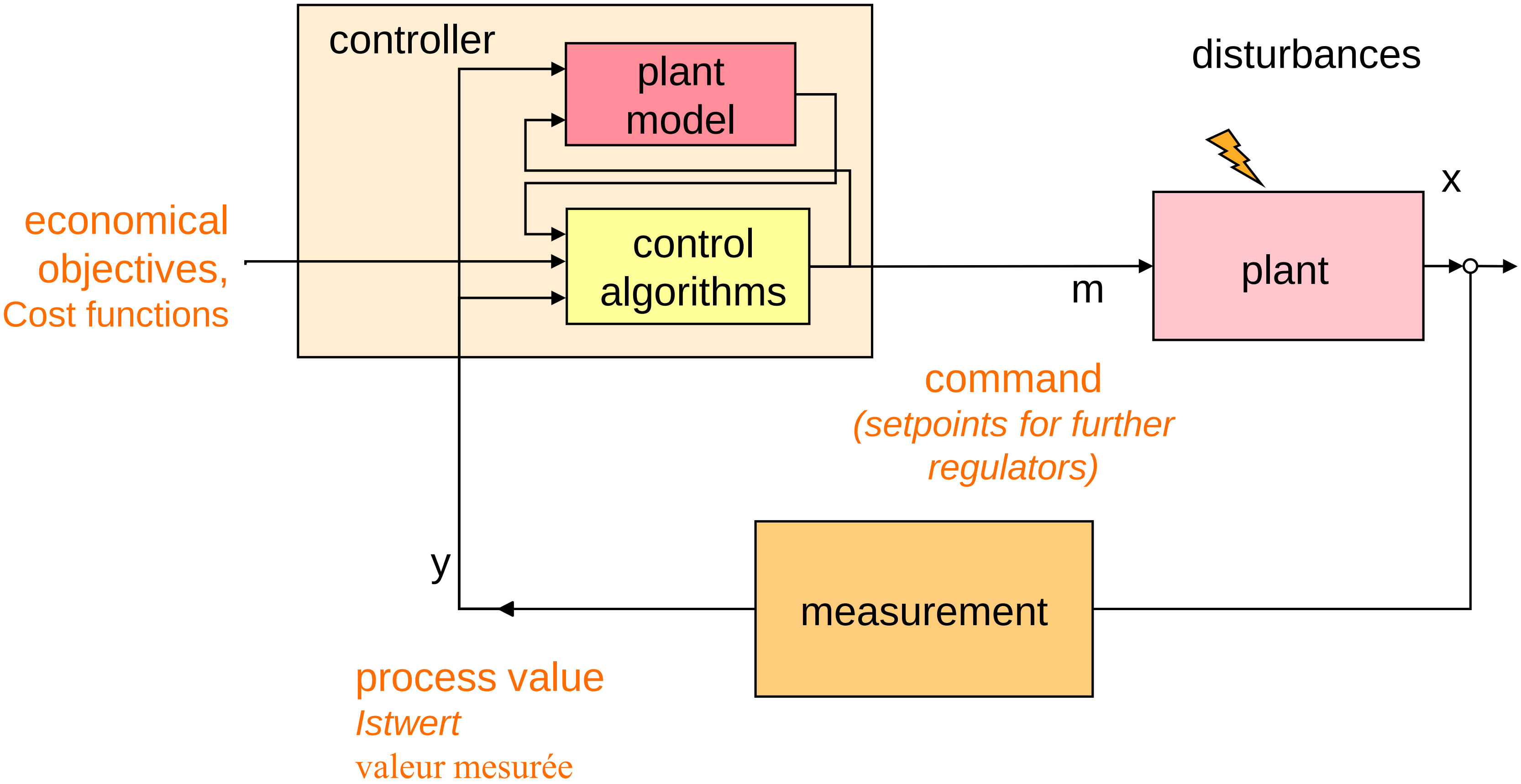
A control system consists often of nested loops,
with the fastest loop at the inner-most level

Feed forward

Basic idea: bring output on good track first, let regulator correct small deviations.
Feed forward controller knows the plant, it can also consider known disturbances



Advanced Control



This is a high-level control in which the set-points are computed based on economical objectives

Exercises

http://tinyurl.com/p6sx4ol

A Control System…

a) is dependent not only on current environment but on past environment as well
b) describes the direction PV moves and how far it travels in response to a change in CO (steady state)
c) set of devices to manage, command, direct or regulate the behavior of other device(s) or system(s)

What is the set point?

a) Variable you want to control
b) Desired value of control variable
c) Signal that is continuously updated

What has only one tuning parameter so it's easy to find "best" tuning, but permits offset?

a) P only
b) PI
c) PD

What is proportional to both the magnitude of the error and the duration of the error?

a) P only
b) PI
c) PD

More Questions ☺

http://tinyurl.com/p6sx4ol

Which statements are correct?

1. Manual tuning is necessary for PID control.
2. Increasing Kp can lead to oscillations.
3. Step response analysis is used when identifying a closed loop plant.

4. For PID control a model of the plant is needed.
5. Feed-forward is a open-loop control technique.
6. In nested control, the inner loop controller reads output(command) of outer loop controller as setpoint.

7. A field bus connects PLCs.
8. The control bus connects the supervisor station with the PLCs.
9. Binary and analog variables are filtered before sampled.

10. PLCs don't support cyclic operation.
11. PLCs may have thousands of inputs and outputs.
12. Two-point controllers are designed for linear systems only.

Solution 1

A Control System…

a) is dependent not only on current environment but on past environment as well
b) describes the direction PV moves and how far it travels in response to a change in CO (steady state)
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What is proportional to both the magnitude of the error and the duration of the error?

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b) PI
c) PD

Solution 2

Which statements are correct?

1. Manual tuning is necessary for PID control. False
2. Increasing Kp can lead to oscillations. True
3. Step response analysis is used when identifying a closed loop plant. True

4. For PID control a model of the plant is needed. False
5. Feed-forward is a open-loop control technique. False
6. In nested control, the inner loop controller reads output(command) of outer loop controller as setpoint. True

7. A field bus connects PLCs. True
8. The control bus connects the supervisor station with the PLCs. True
9. Binary and analog variables are filtered before sampled. True

10. PLCs don't support cyclic operation. False
11. PLCs may have thousands of inputs and outputs. True
12. Two-point controllers are designed for linear systems only. False

Assessment

How does a two-point regulator works ?

How is the a wear-out of the contacts prevented ?

How does a PID regulator work ?

What is the influence of the different parameters of a PID ?

Is a PID controller required for a position control system (motor moves a vehicle)?

Explain the relation between nesting control loops and their real-time response

What is feed-forward control ?

To probe further

"Computer Systems for Automation and Control", Gustaf Olsson, Gianguido Piani, Lund Institute of Technology

“Modern Control Systems”, R. Dorf, Addison Wesley

“Feedback Systems”, Karl Johan Aström, Richard M. Murray
http://www.cds.caltech.edu/~murray/books/AM08/pdf/am08-complete_28Sep12.pdf